S100 31 and 32

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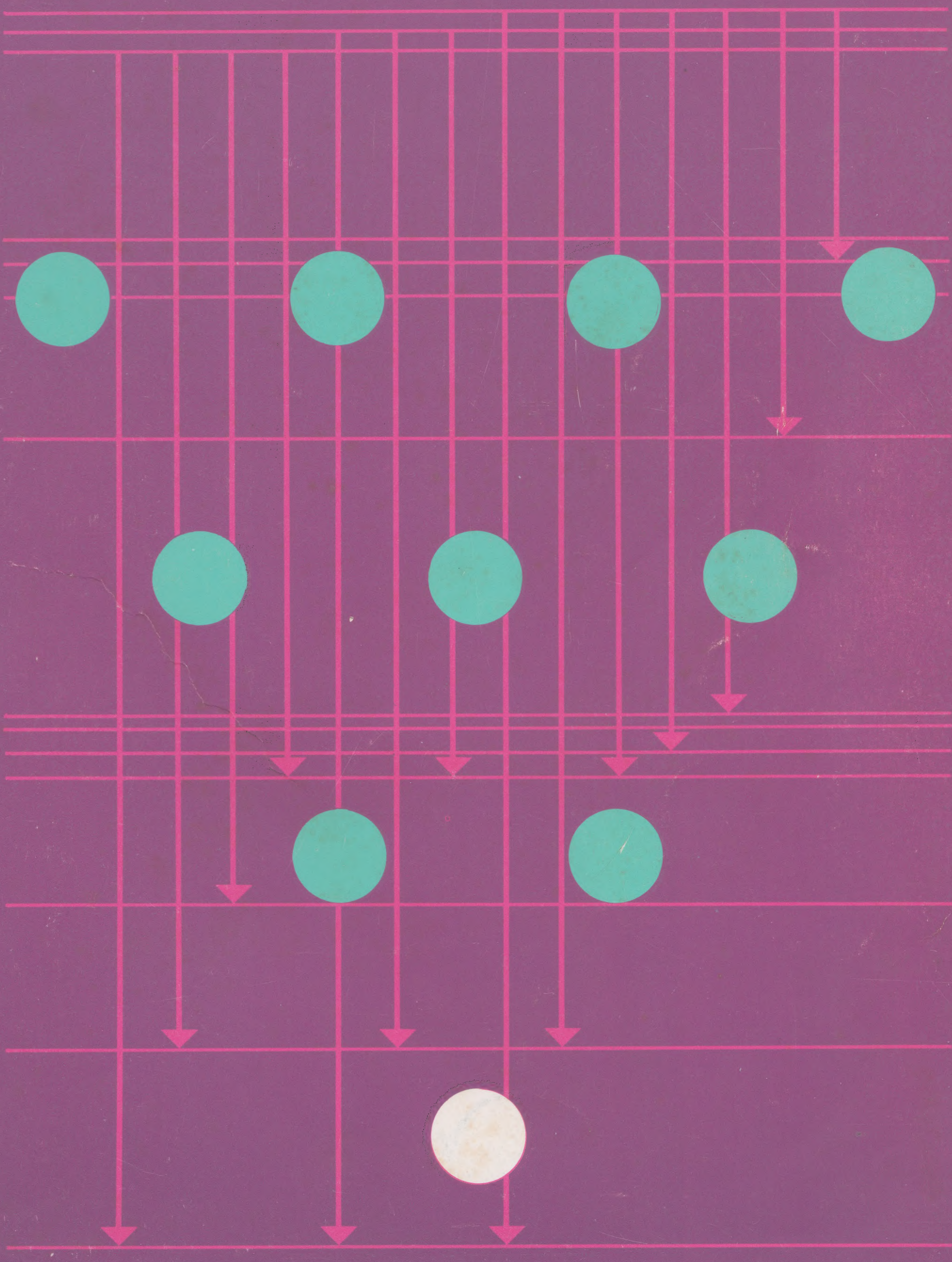
Science Foundation Course Units 31 and 32

The Nucleus of the Atom
Elementary Particles



The Open University

Science Foundation Course Unit 32

ELEMENTARY PARTICLES

Prepared by the Science Foundation Course Team

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Contents

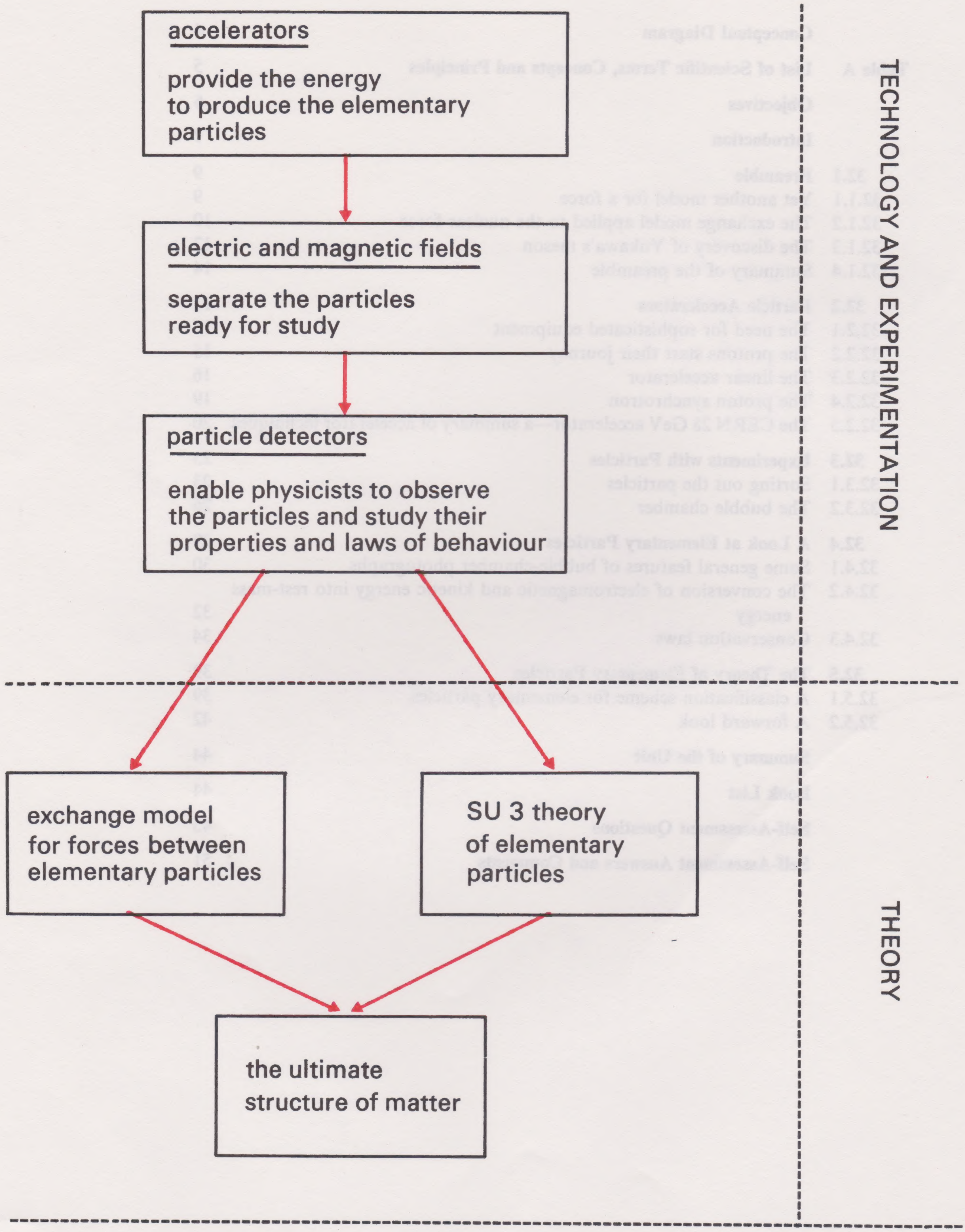
accelerators
provide the energy to produce the elementary particles
electric and magnetic fields
separate the particles ready for study
particle detectors
enable physicists to observe the particles and study their properties and laws of behaviour
exchange model for forces between elementary particles
SU 3 theory of elementary particles
the ultimate structure of matter
TECHNOLOGY AND EXPERIMENTATION
THEORY

Table A

List of Scientific Terms, Concepts and Principles used in Unit 32

Taken as pre-requisites			Introduced in this Unit			
1	2		3		4	
Assumed from general knowledge	**Introduced in a previous Unit**	**Unit No.**	**Developed in this Unit**	**Page No.**	**Developed in a later Unit**	**Unit No.**
	strong interaction	31	meson	12		
	electromagnetic forces and fields	4	elementary particle	13		
	conservation laws:		pion	13		
	of energy	4	linear accelerator	16		
	of momentum	3	proton source	16		
	of electric charge	2	drift tube	17		
	rest-mass energy	4	magnetic curvature of path proportional to particle's momentum	19		
	kinetic energy	4	proton synchrotron	19		
	uncertainty relation	29	bending magnet	24		
	electron-volt	4	electrostatic separator	25		
	nucleon	6	bubble chamber	26		
	voltage	4	bubble growth initiated by charged particles	26		
	frequency	2	superheating	26		
	ionization	6	dependence of boiling-point temperature on pressure	27		
	temperature	5	electron pair	32		
	electron	2	positron	32		
	photon	29	dependence of bubble density on particle velocity	34		
	Compton scattering of photons	29	conservation laws:			
	periodic table of elements	7	of baryons	35		
			of strangeness	36		
			SU3 classification of elementary particles	39		
			quarks	42		

Objectives

When you have completed the work of this Unit, you should be able to:

1 Define, or recognize adequate definitions of, or distinguish between true and false statements concerning each of the terms, concepts and principles in column 3 of Table A.

2 Distinguish between true and false statements concerning the principles of operation of a linear accelerator, a proton synchrotron and a bubble chamber.

3 Solve qualitative problems on the deflection of particles moving in electric and magnetic fields.

4 Make simple deductions concerning the momentum, electric charge, mass and velocity of particles causing tracks in a bubble chamber.

5 Apply the laws of conservation of strangeness, electric charge and baryons to various reactions (without it being necessary to remember the names and properties of the particles involved).

6 Given the values of the electric charge that can be carried by a particle, deduce the value of $(Q-\overline{Q})$ for the particle when it carries a particular charge.

7 Recognize the arrays representing SU3 groupings of 8 and 10 particles on a plot of strangeness versus $(Q-\overline{Q})$. Use such arrays to deduce the properties of missing particles.

Introduction

The study of elementary particles is the study of the structure of matter. It is appropriate that as our Foundation Course draws to its close we should turn to this most basic of modern scientific endeavours.

In this Unit you will learn how quantum behaviour, relativity and nuclear physics merge to create the fascinating world of microphysics. You will see for yourself violent collisions giving birth to particles possessing unfamiliar properties—properties with names like 'strangeness'. You will be led to question whether particles like protons and neutrons are really the fundamental basic building blocks of matter, or like atoms, merely composite structures built out of something yet more elementary.

The subject of elementary particles is often regarded as too 'theoretical', too 'abstract' to be really understood except by a handful of experts. Up to a point this is so. A full appreciation of the subject requires a grasp of advanced mathematics. Nevertheless we hope to show you that it is possible to go quite far into the subject before lack of mathematics becomes a bar to further progress. True, one needs a certain background knowledge of physics in order to make a start—but this background knowledge you have now acquired from the earlier parts of the Course.

By the end of the Unit you will have learnt that it requires only familiar things like hydrogen gas, electric and magnetic fields, and boiling liquids to produce and detect these particles. The technology involved is impressive, but the basic principles are easily understood. And as for this peculiar property called strangeness, by the end of the Unit not only will you understand why it is necessary to introduce such a concept, but you will also be able to deduce for yourself the strangeness values of the particles.

The Unit begins with an extended preamble. The purpose of this first section is to set the scene. It does so by describing the theory that started it all. The work of the Unit really begins with sections 2 and 3. These are devoted to a description of the remarkable tools of the high-energy physicist—particle accelerators and bubble chambers; it is with these that he produces new particles and studies their subsequent behaviour. In the fourth section, we give you a feel for the kind of discoveries that have been made. This is done in a rather novel way—in the form of a 'guided tour' of the world of elementary particles, as seen through bubble-chamber stereo-photographs. Finally we discuss where the subject might eventually lead.

Study Comment

Although you will be required to answer some questions which involve many particles and their properties, you are not required to remember or recognize the names or properties of any of them. These particular questions have been designed to test whether you know how to apply a few very simple rules of behaviour – the names and properties of the particles will be given to you as and when required.

32.1 Preamble

32.1.1 Yet another model for a force

You may remember from Unit 4 how difficult it was to 'explain' the concept of force. You learnt that it was something one *infers* from motion —when a particle moves in a certain way, it is said to be acted on by a force.

Various models of fields and forces were described—balls on rubber membranes and corks bobbing up and down on water. No one suggests these models are in any sense adequate, but from time to time they can be useful to illustrate a point. We now introduce you to yet another model. At first it will strike you as quite bizarre. Nevertheless, as you will soon learn, it has proved extraordinarily useful and successful.

Imagine you are an astronaut assigned to the task of exploring a new planet. You have arrived in the vicinity of the planet and have gone into orbit around it. As you look down, you see that large patches of the surface are green. On one of these green patches are two unidentified white objects—they are so far away they look like two white dots (Fig. 1 (a)). As you watch them you note that their separation, although it varies, never exceeds a certain maximum value. Other white dots come on to the green patch and move about singly—all except one which happens to pass close to the original two (Figs. 1 (b) and 1 (c)). When it comes within range of this maximum separation, its motion is arrested (Fig. 1 (d)). From that point onwards it stays close to the other two (Figs. 1 (e) and (f)).

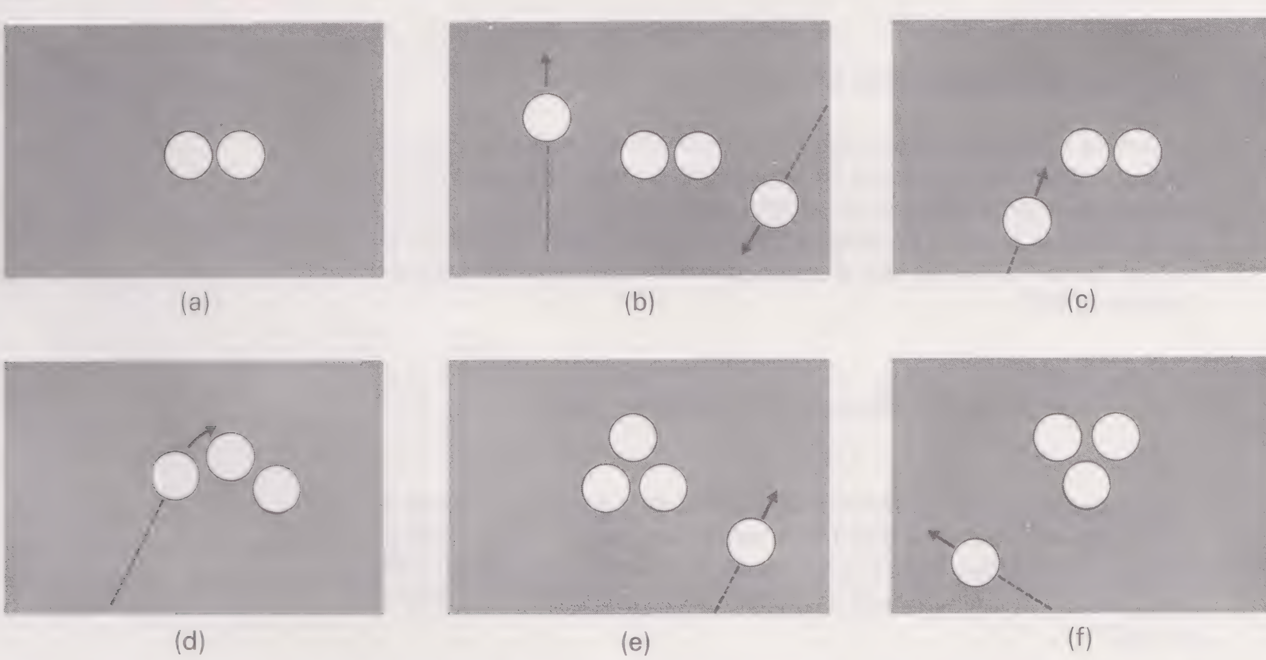

Figure 1 The behaviour of white objects on the surface of a hitherto unexplored planet.

What might you conclude from the behaviour of these dots? Is it reasonable to postulate a force of some kind acting between the white objects?

Yes, indeed. A force acting between the white objects would be a very reasonable way of describing their behaviour. The original two objects

were constrained to stay within a certain distance of each other because of a force of attraction between them. The newly arrived object happened to come within the range of this force and that is why it stuck to the other two. Indeed this force looks very much like the short-ranged nuclear force, or strong interaction, which we were discussing in Unit 31, and also like the force holding atoms together in solids and liquids (Unit 5).

In order to investigate the nature of the white objects and the force acting between them, you decide to descend and land on the green patch. What will you find—white balls with springs, or rubber cords stretched between them (Fig. 2)?

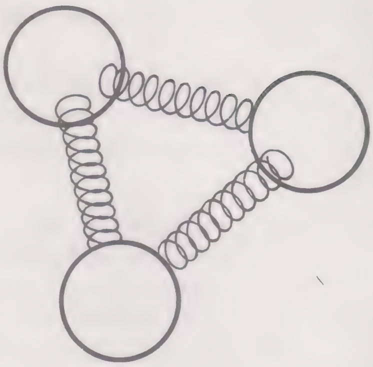

Figure 2 Could this be the kind of force acting between the white objects?

On landing, you find that the planet is exceedingly civilized—you have arrived in time for the start of a cricket match. Most of the players are just strolling around, but in one corner of the field there are three of them conscientiously practising their throwing and catching. Originally of course there were only two—as the third passed by he was thrown the ball and in that way joined them. You are now able to see that the maximum separation of the cricketers, i.e. the range of the supposed force, was nothing more mysterious than the maximum distance the ball could be thrown (Fig. 3, p. 12).

Suppose the cricketers decide to practice with a much heavier ball, what effect would this have on the characteristics of the 'force'?

The heavier the ball, the shorter would be the range of the force (Fig. 4). Thus it is concluded that:

> *a process involving the exchange of an intermediary object may give rise to effects similar to those produced by a force.*

Forces that can be described in this way are not surprisingly called *exchange forces*.

exchange forces

32.1.2 The exchange model applied to the nuclear force

No one, of course, would seriously want to introduce the idea of cricketer-cricketer attractive forces. But the question does arise as to whether one ought to look at phenomena commonly called 'forces' and see if they can be described in terms of exchange processes. In particular, how about the nuclear force? This was the question posed by the Japanese physicist Yukawa in 1935.

What two important characteristics has the nuclear force?

As you learnt in Unit 31, the nuclear force is strong and has a range of only about 10^{-15} m. Is it possible to relate the mass of a supposed exchanged intermediary to this range, in the same way as the range of the hypothetical cricketer-cricketer interaction was governed by the mass of the ball?

Before answering that question, we must first consider a more fundamental one—how is it possible for the nucleons to exchange anything *at all*? If the two nucleons are at rest, their only energy is their rest-mass energy, so where do they find energy (i) to make the rest-mass of the intermediary object and (ii) to give it enough kinetic energy to go across the gap between them? The law of conservation of energy would appear to rule against it.

At this point, Heisenberg's uncertainty relation, involving uncertainty in energy, ΔE, and uncertainty in time, Δt, puts in an appearance:

an application of Heisenberg's uncertainty relation

$$\Delta E\ \Delta t \approx h/4\pi \quad\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

In Unit 29, we were at pains to point out that the law of conservation of energy can be experimentally verified only to within the limits allowed by this relation. There is no evidence to support a view that the energy of a system must remain exactly constant at all times. If one finds it useful to postulate that the energy of the system might fluctuate by an amount ΔE for a length of time Δt, such a postulate could never run counter to any experimental evidence. (It might be a good idea to look back over section 29.4.1 of Unit 29 to refresh your memory as to the nature of this argument.)

Thus Heisenberg's relation makes it possible to suggest that the energy of the two-nucleon system could fluctuate by an amount ΔE for a period Δt. There could be a large fluctuation for a short time, or alternatively a smaller fluctuation for a longer time. The two nucleons could therefore 'borrow' energy ΔE on a long-term or short-term loan (naming Heisenberg as surety). This energy could then go towards creating an intermediary object which on being exchanged somehow produced the nuclear force. Once the exchange was completed, the process could be repeated again and again, so the force would apparently operate continuously.

We now return to the earlier question—can we from the range of the force discover the mass of the supposed intermediary particle? We can arrive at some idea of this quite quickly from the known separation of the nucleons, R, if we use equation 1. The intermediary cannot cross the gap between two nucleons in zero time. It follows from the work of Units 3 and 4 that no object can travel faster than c, the speed of light.*

Thus the minimum time, Δt, for which the loan of energy is required is the time taken to travel a distance R at a speed c:

$$\Delta t = R/c \quad\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

(If the speed is lower, the time interval must of course be longer.) Corresponding to this minimum time interval, there is a maximum energy that can be borrowed, and this is given by substituting Δt in equation 1:

$$\Delta E.\ \frac{R}{c} \approx h/4\pi$$

i.e.

$$\Delta E \approx \frac{hc}{4\pi R} \quad\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

Calculate ΔE in electron-volts, using the following values:

$h = 6.6\times10^{-34}$ J s
$c = 3\times10^{8}$ m s^{-1}
$R = 10^{-15}$ m
1 electron-volt $= 1.6\times10^{-19}$ joule

$$\Delta E \approx \frac{6.6\times10^{-34}\times3\times10^{8}}{4\pi\ 10^{-15}}$$

$$\approx 16\times10^{-12}\ \text{joule}$$

$$\approx \frac{16\times10^{-12}}{1.6\times10^{-19}}\ \text{eV}$$

$$\approx 100\times10^{6}\ \text{eV}$$

$$\approx 100\ \text{MeV}$$

(Remember you were introduced to electron-volts as a unit of energy in Unit 4.)

It should be remembered that the estimate of 100 MeV for ΔE is very crude. This is because equation 1 is only approximate.

* *You may remember that the momentum of an object is given by* $p = m_0 v_{im}/(1 - v_{im}^2/c^2)^{\frac{1}{2}}$ *where* m_0 *is the rest-mass and* v_{im} *is the improper velocity (i.e. the velocity of the object as usually measured in the laboratory frame of reference). As the object travels faster, so its momentum increases. The expression shows that* p *becomes infinite as* v_{im} *approaches* c. *Thus no object can be accelerated to a velocity exceeding that of light.*

This calculation suggests that when nucleons are separated by a distance of 10^{-15} m they can exchange an intermediary with an energy up to 100 MeV. If they are closer than 10^{-15} m, then the time required for the exchange, Δt, is smaller and the uncertainty relation allows ΔE to be correspondingly higher. But what if the nucleons are much further apart than 10^{-15} m? As you already know—the force drops to zero. For our model of exchange forces, this implies that, for one reason or another, the exchange process ceases. One way of explaining this is to postulate that whereas the intermediary object can have energy 100 MeV or more, *it cannot have less than* 100 *MeV*.

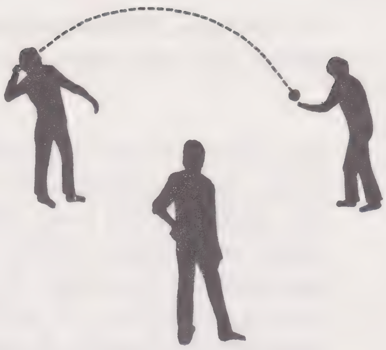

Figure 3 In order to exchange a ball, the players must remain within a certain range of each other.

An object can always be given *more* energy by giving it extra kinetic energy; but why do you think this particular object can never have *less* than 100 MeV?

The indication is that *the intermediary particle has a rest-mass corresponding to an energy of* 100 *MeV*. In order for the particle to exist, it must have at least 100 MeV for its rest-mass. If the separation of the nucleons is sufficiently great that Δt in equation 1 requires ΔE to be less than 100 MeV, the particle cannot be exchanged and the force disappears.

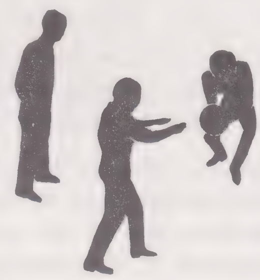

Figure 4 The heavier the ball, the closer the players must be.

This then was the substance of Yukawa's remarkable theory. He introduced an entirely new particle. It had a rest-mass energy of about 100 MeV, or if you like, a mass some 200 times that of the electron (the mass of an electron is equivalent in energy to about 0.5 MeV). Because this particle had a mass intermediate between that of the nucleons and electrons it was called a *meson* (from the Greek word 'mesos', meaning 'in the middle').

32.1.3 The discovery of Yukawa's meson

meson

Of course, the meson, as it has been presented to you so far, is a rather ethereal object! If it exists at all, it comes and goes, its fleeting existence being permitted only by the uncertainty relation.

Its energy, ΔE, must be returned before the time Δt elapses. Like Cinderella, it is allowed out only on condition that it is back home on time! Thus far, the idea that the nuclear force is due to the exchange of mesons is nothing more than a theoretical model. But Yukawa went further.

Suppose the meson did not have to rely on the uncertainty relation for the energy it needed for its rest-mass—suppose there were some other supply of energy to hand. It would then no longer be necessary to return the energy after a limited time Δt, and the meson could take on a separate and more permanent existence. Such a situation exists when nucleons, instead of being stationary, are involved in a violent collision. The energy of the two-nucleon system is now greater by virtue of the kinetic energy possessed by the original particles. The nuclear force comes into operation at the moment of impact. The meson is now exchanged under conditions where a great deal of energy exists, and it can take some of the kinetic energy of the two nucleons for its rest-mass energy. The law of conservation of energy can be rigorously obeyed in as much as the energies before and after the collision can be the same, even though a meson has now been brought into existence:

$$\underbrace{Mc^2+Mc^2+T_1+T_2}_{\text{(before the collision)}} = \underbrace{Mc^2+Mc^2+mc^2+T'_1+T'_2+T'_\mathrm{m}}_{\text{(after the collision)}} \quad \ldots\ldots \quad (4)$$

where M is the mass of each nucleon and Mc^2 is the equivalent rest-mass energy (see Unit 4); T_1 and T_2 are the initial kinetic energies of the nucleons and T'_1 and T'_2 are the final kinetic energies; mc^2 is the rest-mass energy of the meson and T'_m its kinetic energy.

A proton of kinetic energy 1 000 MeV strikes a stationary nucleon. After the collision, the kinetic energies of the two nucleons are 500 and 200 MeV. What is the kinetic energy of the meson produced in the collision? (Assume it has a mass, m, such that $mc^2 = 100$ MeV.)

$Mc^2 + Mc^2$ cancels out on both sides of the equation. $mc^2 = 100$ MeV, $T_1 = 1\,000$ MeV, $T_2 = 0$, $T'_1 = 500$ MeV, $T'_2 = 200$ MeV

$\therefore\ 1\,000 + 0 = 100 + 500 + 200 + T'_m$

$\therefore\ T'_m = 200$ MeV

Therefore, on the basis of Yukawa's model, it was possible to predict that in a violent nuclear collision, in which sufficient energy was available to create the necessary rest-mass, a physically detectable meson might be produced (see Fig. 5).

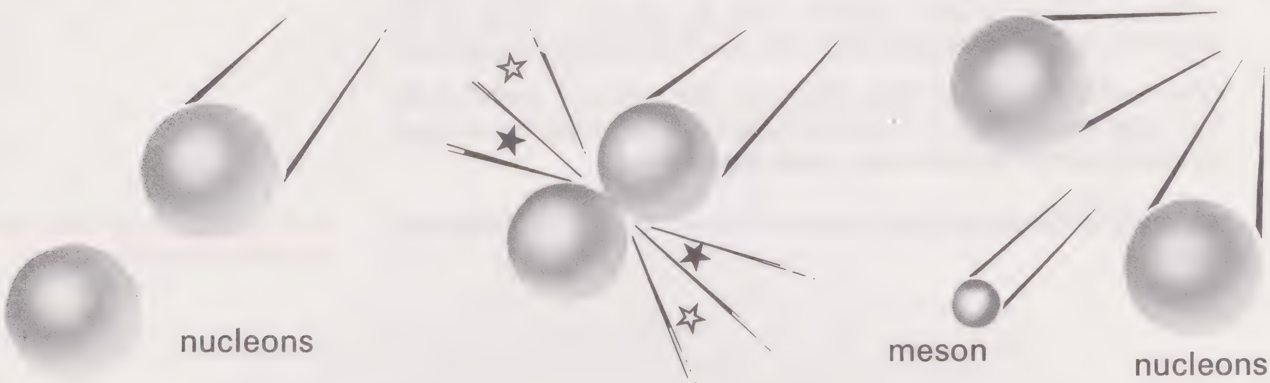

Figure 5 In high-energy nuclear collisions, mesons may be produced.

the discovery of Yukawa's meson—the pion

This prediction was triumphantly vindicated in 1947 by Powell, Occhialini and Lattes with the discovery of Yukawa's meson—now called the π-meson, or *pion* for short. Its mass of 273 times the electron mass (or in energy units, 139 MeV) was very close to that predicted by Yukawa. The way to a clear understanding of nuclear forces seemed at that time straight-forward. All one had to do was to produce pions, study the new particles' properties and observe how they were scattered and absorbed by nucleons.

elementary particle

This mood of optimism was soon shattered. In the same year that the pion was discovered, *another* and heavier particle was found among the debris of a high-energy nuclear collision. Then more and more appeared. Today the nuclear scientist is confronted by a bewildering array of about 200 so-called 'elementary' particles. (The words 'elementary' and 'fundamental' are used interchangeably in connection with these particles. An *elementary particle* is one that cannot be described as a composite structure of more basic components. Incidentally, the choice of the word 'elementary' might suggest that the properties of these particles are simple—nothing however could be further from the truth!)

The model whereby nucleons exchange a pion tells only part of the story. It may be adequate for nucleons separated by 10^{-15} m, but when nucleons are closer it appears that much heavier objects can be exchanged as well.

One of the new particles is found to have a rest-mass energy of 550 MeV. If pion exchange extends to 10^{-15} m, how close do the nucleons have to be in order to be able to start exchanging this other particle?

The mass of this other particle is about 4 times greater than that of the pion, so the separation of the nucleons must be correspondingly smaller, i.e. 0.2 to 0.3×10^{-15} m.

A proper understanding of the nuclear force then seems to entail an understanding of the behaviour of all these new elementary particles. This would be impossibly complicated if it were not for the existence of certain simplifying rules and patterns of behaviour; we shall discuss these towards the end of the Unit, having first described how elementary particles are produced and detected in the laboratory.

32.1.4 Summary of the preamble

A new model for describing forces has been introduced. According to this model, a force acting between two or more objects may be represented by the exchange of some intermediary between them.

This model has been applied to the nuclear force. From the uncertainty relation and the known range of the force, the mass of the intermediary, called a pion, could be determined; it is 273 times the mass of the electron (i.e. has a rest-mass energy of 139 MeV).

When sufficient energy is available, as it is in a very violent nuclear collision, some of it may transform into the rest-mass energy of the intermediary pion which can thereby take on a real and separate existence.

Other particles have also been discovered. The exchange model of the force must therefore be developed further to allow the nucleon to exchange additional heavier particles during close approaches.

The study of the nuclear force therefore becomes the study of elementary particles.

the study of the nuclear force becomes the study of elementary particles

Figure 6 An aerial view of CERN, Geneva. [Photo: CERN]

32.2 Particle Accelerators

32.2.1 The need for sophisticated equipment

There are two basic experimental requirements before elementary particles can be produced and their behaviour studied.

What do you think these basic requirements might be?

In the first place the physicist needs a source of highly energetic nuclear particles, such as protons, with which to bombard other protons and produce the new particles. The energy must exceed several thousand MeV to be of interest—this figure being set by the masses of the heaviest particles he wishes to produce. (To appreciate how large this energy is, you should note that the typical kinetic energy of an atom moving about at room temperature is only a few hundredths of an electron-volt.)

Secondly, it is necessary to have devices capable of detecting particles as small as a nucleus, moving with speeds approaching the maximum value, i.e. the speed of light. This means extending the senses to the very frontiers of small-scale and rapidly changing observations (Unit 2).

In response to the demands of the high-energy physicist (i.e. a physicist who studies elementary particles), technologists have produced some of the world's most remarkable machines—the particle accelerators. These are now so complex and costly that only the U.S.A., Russia, and lately Japan, can afford to finance them alone; the European nations have to pool their efforts and share a common facility in Geneva, Switzerland at CERN (Conseil Européen de la Recherche Nucléaire).

In this section we give a description of the principles of these machines. In this Unit's television programme we shall take you on a visit to CERN (Fig. 6) to show you the actual equipment.

32.2.2 The protons start their journey

It is not difficult to get an accelerated beam of protons of low energy (up to 1 or 2 MeV).

Think back over the Course. Can you remember a previous occasion when an accelerated beam of positive ions was obtained?

In Unit 6 it was described how, in the mass spectrometer, an electric discharge passing through a gas, ionized the gas atoms. The positively charged ions could then be accelerated by subjecting them to an electric field. Exactly the same idea is used again here. In the *proton source*, hydrogen gas is ionized so as to give free protons. The principle is illustrated in Figure 7. These are then subjected to an accelerating voltage. An energy of say 1 000 MeV would be achieved by accelerating the protons through a voltage difference of . . .

how many volts?

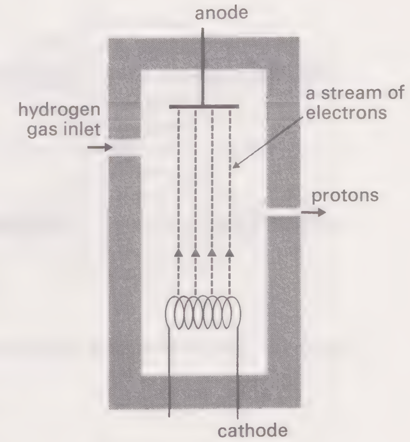

Figure 7 A source of protons. Hydrogen gas enters and is ionized in an electrical discharge.

1 000 MV. (Refer if necessary to Unit 4.) This is the first major problem—it is quite impossible in the laboratory to sustain an electric field capable of giving a voltage difference of anything like this amount. In practice it has proved impossible to exceed about 10 MV.

a barrier to further acceleration

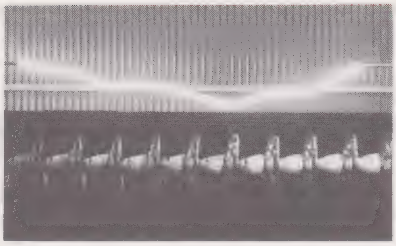

Figure 8 Electrical discharges like this one set a limit on the voltage differences that can be realized in practice.

Can you guess why?

Long before one gets to the kind of voltage that interests a high-energy physicist—lightning strikes! With a deafening bang the high-voltage electrodes discharge, either to each other or to the surroundings (Fig. 8).

'Brute force' is therefore no answer. Somehow the protons must be coaxed to go at a speed corresponding to an enormous voltage, *without the use of such a large voltage.*

32.2.3 The linear accelerator

linear accelerator

This can be achieved in a *linear accelerator*, a name often contracted to *linac*. It consists of a series of cylindrical metal tubes arranged along a common axis. They are connected to a voltage supply as shown in Figure 9.

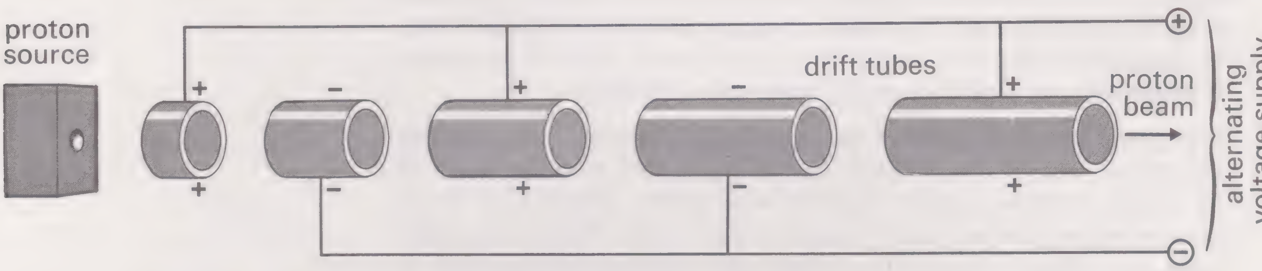

Figure 9 A schematic diagram of a linear accelerator. The protons are repeatedly accelerated in small stages as they cross the gaps between the drift tubes.

The whole system is evacuated so that the protons from the source can pass down the axis of the tubes and suffer little scattering from air molecules. To see how the protons are affected by the voltages on the tubes, take a look at Figure 10 where the configuration of the electric fields is shown.

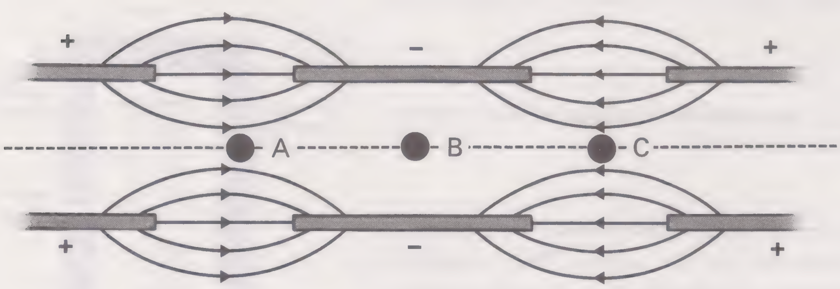

Figure 10 The electric field configuration in a linear accelerator.

Assuming the proton moves from left to right along the axis in Figure 10, what change if any do you expect to its velocity in each of the regions labelled A, B and C?

As the proton crosses the gap between the tubes at A, the direction of the electric field is such as to increase its velocity. At C the field is in the opposite direction and in this region the proton would tend to slow down. When the proton is well inside a tube, for example at position B, there is no field so the proton 'drifts' for a while at constant velocity—for this reason the tubes are called *drift tubes*.

drift tubes

What is the net effect on the proton's velocity in passing from A to C?

Nil! The trouble of course is that the slowing down in region C exactly compensates for the acceleration at A. Fortunately, it is possible to do something about this. While the proton is drifting in the field-free interior of a tube, the polarity of the voltage supply (see the right-hand side of Fig. 9) can be switched—the tubes that were positive now become negative and vice versa. This can be achieved without in any way affecting the proton's motion.

If this change in polarity occurs while a proton is at position B in Figure 10 what will happen to it when it emerges from the tube at C?

The change in polarity converts retarding fields into accelerating ones and vice versa. *A proton originally accelerated across the gap at A, finds itself again accelerated at the next gap C.* (See Fig. 11.)

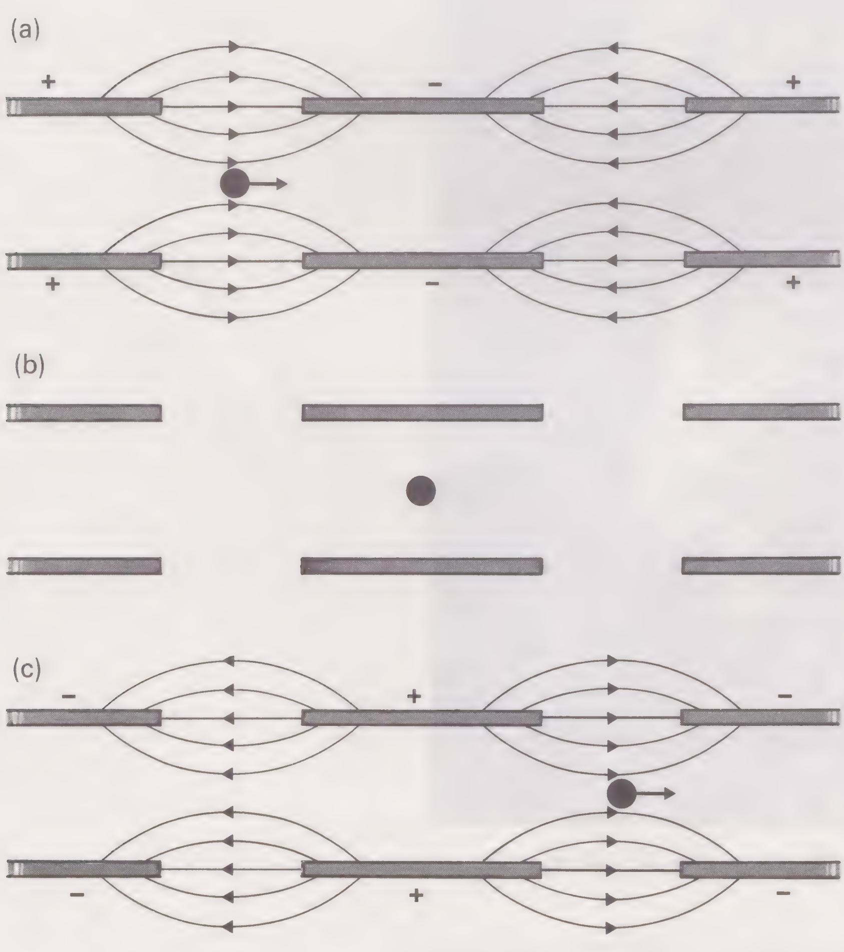

Figure 11 Successive field configurations as a proton moves from one gap to the next.

If the voltage between the tubes is 50 kV, what is the net gain in energy of the proton after it has crossed two gaps?

It gains 50 keV at each gap, so the total is 2×50 keV = 100 keV.

The polarity of the voltage can be switched repeatedly by an alternating voltage supply so that the process can be continued. The proton gains an increment of energy corresponding to the voltage difference between the tubes each time it crosses a gap. If the voltage difference is V volts, the energy of a proton that has crossed n gaps is nV electron volts.

Take another look at Figure 9. What difference do you notice in successive drift tubes? Why should there be this difference?

If the voltage polarity changes at regular intervals (i.e. at constant frequency), the drift tubes must become progressively longer to allow for the proton's increasing speed—otherwise they would get out of step with the accelerating field across the gaps.

(In modern linear accelerators, the voltages are not applied in quite the way we have described here. The tubes are mounted along the axis of a hollow cylindrical cavity (shown opened in Figure 12), and currents of a suitable distribution are set up in the walls of the cavity to produce the fields. Such an arrangement leads to an improved electrical efficiency. The details of this refinement need not concern you, however, because the principle remains the same—the protons are progressively accelerated at each gap.)

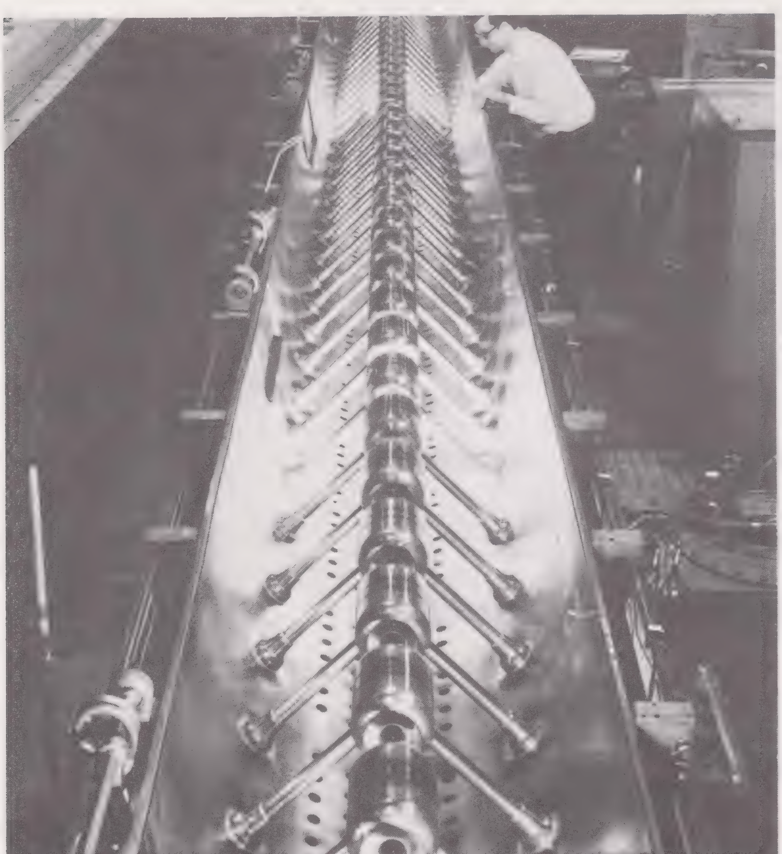

Figure 12 Part of a linear accelerator opened up to show the drift tubes. The proton source is at the far end.

The way is now open to enormous energies—at least from the technical point of view. All we have to do is to have lots and lots of drift tubes. But a problem of another kind arises at this point.

The linear accelerator in Figure 12 delivers protons of energy 50 MeV. The CERN machine was to reach an ultimate energy of 28 GeV, i.e. 28 000 MeV (1 Gev ≡ 10^3 MeV ≡ 10^9 eV). This could have been reached by simply extending the linear accelerator further, but what kind of problem do you think would have been encountered?

Certainly one important problem would have been that of money—how many miles of accelerator can a government be persuaded to finance! (As a matter of interest, the longest linear accelerator in the world is a machine for accelerating electrons to 20 GeV at Stanford, California; it is two miles long.)

a further barrier to the achievement of greater energies

32.2.4 The proton synchrotron

proton synchrotron

The synchrotron introduces another ingenious idea in accelerator design, one that allows high energies to be achieved more economically than by extending a linear machine. In the synchrotron, the protons are made to travel many times around a circle of constant radius. (They must, of course, still be travelling in a vacuum.) Cavities are placed at various points around the circumference and these provide electric fields for acceleration. By repeatedly following the same path, the protons are accelerated *many times by the same cavities* (see Fig. 13).

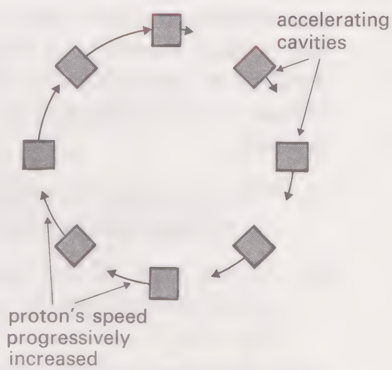

Figure 13 In a proton synchrotron, the protons are repeatedly accelerated by the same cavities.

In order to keep the protons on the circular path, a centripetal force must be provided at right-angles to their motion. You will remember that in a mass spectrometer (Unit 6) the heavy ions were deflected by a magnetic field. The same also holds in a proton synchrotron; a vertical magnetic field steers the protons along their horizontal circular path (see Figs. 14 and 15).

Just as in the mass spectrometer, *the deflection produced by a magnetic field of a given strength is such that the radius of curvature of the particle's path is proportional to the particle's momentum.* (This is an important relationship which you should remember.)

If the protons are to be accelerated, *and yet remain on a path of constant radius*, what must happen to the magnetic field?

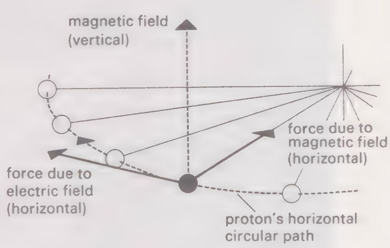

Figure 14 In a synchrotron, the proton is accelerated by electric forces acting tangentially to its circular path. Meanwhile the magnetic field exerts the necessary restraining force directed towards the centre of the circle.

In order to keep the accelerating protons moving along the same path in the synchrotron, the strength of the magnetic field must be progressively increased. This is achieved by progressively increasing the electric current in the windings of the electromagnets during the acceleration period.

As the proton moves faster, the time it takes to arrive at each successive accelerating cavity becomes shorter and shorter. In the linear accelerator it is possible to make the distance between the successive accelerating gaps longer so that the proton does not get out of step with the fixed frequency accelerating voltage. This is not possible in the synchrotron because the proton traverses the *same* cavities many times and on each occasion at a different speed.

How do you suggest the proton's arrival at the accelerating cavities could be kept in step with the alternating voltage?

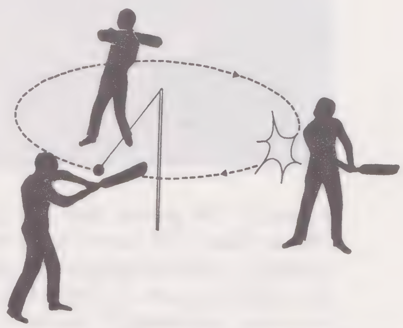

Figure 15 An analogy for a synchrotron.

The answer is to abandon the idea of a *fixed* frequency alternating voltage. Instead the frequency is progressively increased so as to keep exactly in step with the arrival of the protons at the cavities; in short, they are synchronized—hence the name of the machine. Does this mean that we

are now able to reach any energy we like by simply sending the protons round and round repeatedly? Unfortunately, no. As the protons accelerate they require an ever stronger magnetic field to hold them on course. Finally it becomes impracticable to increase the field any further and no more acceleration can take place—the protons have reached the maximum energy appropriate to the particular accelerator.

Having reached the maximum energy the protons are deflected out of their circular path by the sudden introduction of an additional local magnetic field. They are directed on to a target consisting of a lump of metal. As the protons crash into the nuclei of the atoms of the target material, the new elementary particles are created.

32.2.5 The CERN 28 GeV accelerator—a summary of accelerator techniques

To reach the highest energies, the three accelerating techniques (high voltage, linear accelerator and synchrotron) are combined into one machine, and the protons are accelerated in three stages. We now describe one of these machines—the one at CERN. In so doing we can provide you with a short summary of the previous sections. Incidentally, you are not required to remember any of the numbers quoted in the summary that follows; they are there merely to give you a feel for the orders of magnitude involved.

(i) The protons to be accelerated are produced through the ionization of hydrogen gas in an electrical discharge.

(ii) At the start of the acceleration cycle, the protons are given an initial acceleration by a large voltage difference of 550 kV (see Fig. 16).

Figure 16 *The protons start their journey at CERN in this metal-cladded room, called a Faraday cage. The source is situated in the horizontal cylinder on the left, above the technician. When in operation the source is put at a voltage of* 550 000 *V with respect to the walls of the cage. In the foreground, mounted on ebonite pillars, is a platform housing the control equipment for the source. The protons are fired from the source into the linear accelerator which is situated beyond the far wall.* [Photo: CERN]

(iii) They pass into a linear accelerator. An alternating electric field is set up and this acts upon the protons only when it is in a sense such as to cause acceleration. At other times, the protons are shielded from the electric field by drift tubes. The particles are accelerated in this way to an energy of 50 MeV.

(iv) The protons are injected from the linear accelerator into the synchrotron (see Fig. 17). They are steered in a horizontal circular path of diameter 200 m by a magnetic field produced by electromagnets (Fig. 18). They are accelerated at fourteen points around the circumference of the circle by electric fields. A drawing of a section of the synchrotron is shown in Figure 19.

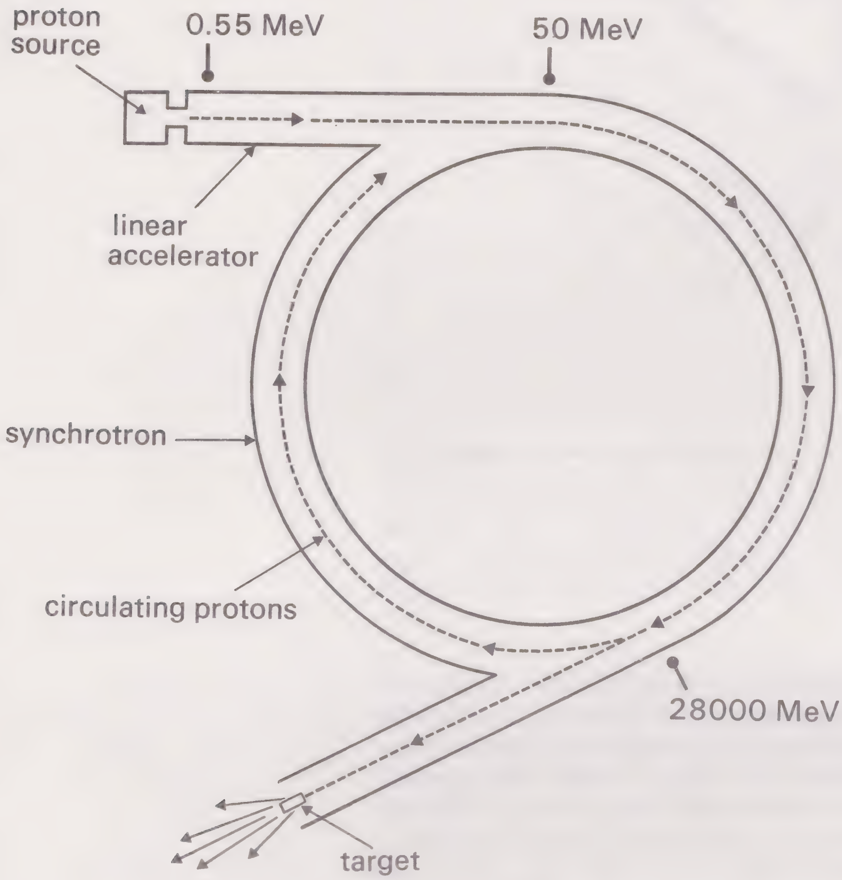

Figure 17 The CERN 28 GeV accelerator. It combines three types of acceleration: high voltage, linear accelerator, and synchrotron. On reaching the maximum energy the protons are ejected and strike a target, producing secondary particles.

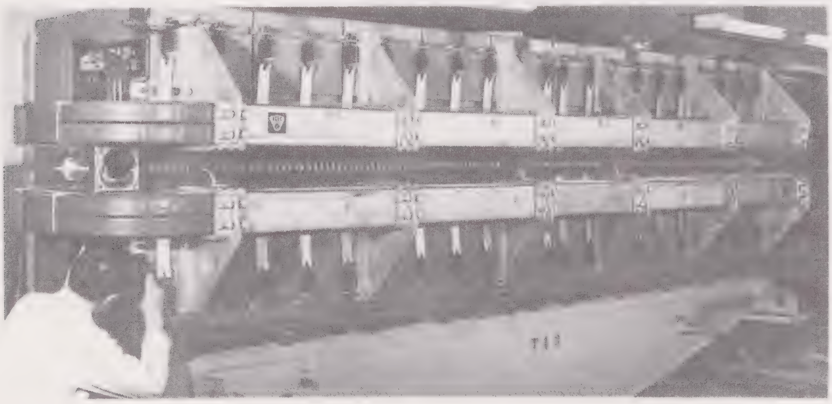

Figure 18 One of the 100 32-ton electromagnets used for steering protons around the 200 m diameter ring of the CERN synchrotron. Passing along the centre of the magnet you can see the evacuated tube within which the protons travel. [Photo: CERN]

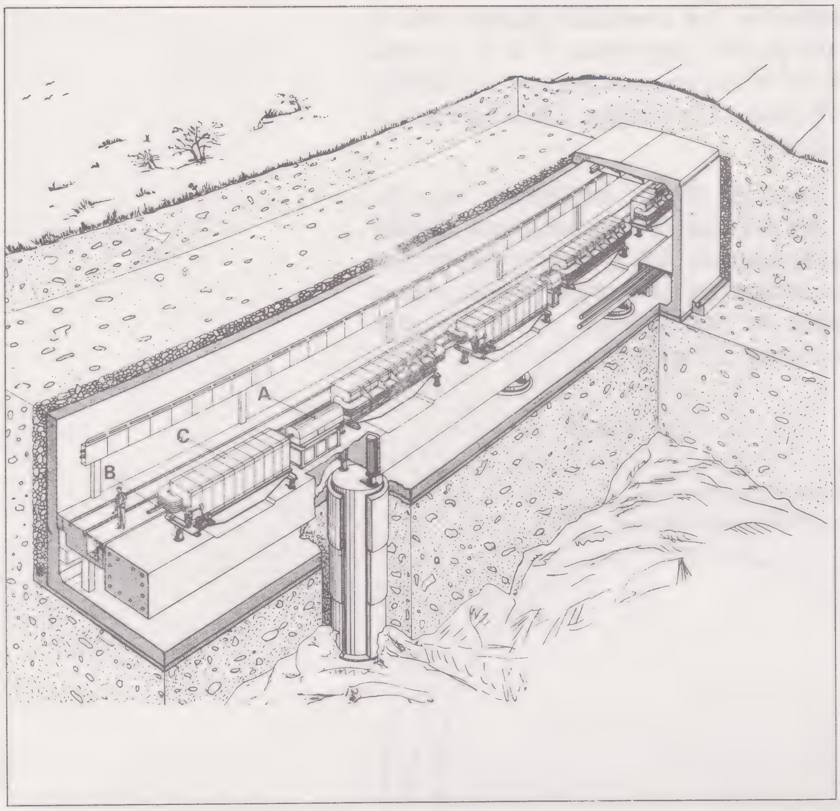

Figure 19 *A section of the synchrotron at CERN. B is the evacuated tube through which the protons pass. C is one of the fourteen accelerating cavities distributed around the ring. A are electromagnets. The machine is housed in an underground tunnel to make it easier to confine the stray radiation produced during its operation. The alignment of the magnets has to be maintained to a fraction of a millimetre. For this reason they rest on a concrete base which is itself elastically supported by massive columns standing on firm bed-rock.*

The magnetic field is progressively increased in order to keep the protons on course, and the frequency of the alternating electric field is increased to keep in step with the accelerating protons. The acceleration cycle is completed in a total of about two seconds. In this time the protons have been round the synchrotron 480 000 times (a distance equivalent to going several times round the Earth). On reaching their maximum energy of 28 GeV the protons are ejected from the machine.

(v) Another batch of protons is admitted and the process repeated.

(vi) The net result is that about 10^{12} protons, each of energy 28 GeV, are emitted in bursts at two-second intervals. These are directed on to a metal target.

Try SAQs 1 *to* 7.

32.3 Experiments with Particles

32.3.1 Sorting out the particles

Once the elementary particles have been produced in the target, the next problem is to investigate their properties. This is best done by separating out one particular type of particle at a time from all the others. Having studied that particular particle, one can then systematically move on to consider the next. In this Unit's main home experiment, you will be concentrating on a particular investigation with certain limited objectives in mind. For this to be possible, pions had to be separated out from all the other particles and nuclear debris coming away from the target. But how was this done? How can one get rid of all the other particles, and leave only those with the desired mass, momentum and electric charge, all moving in the desired direction?

A start may be made by isolating those particles moving in one chosen direction.

Can you guess how this might be achieved?

This can be done with the help of a heavy shielding wall in which there is simply a small hole to let the particles through (see Fig. 20).

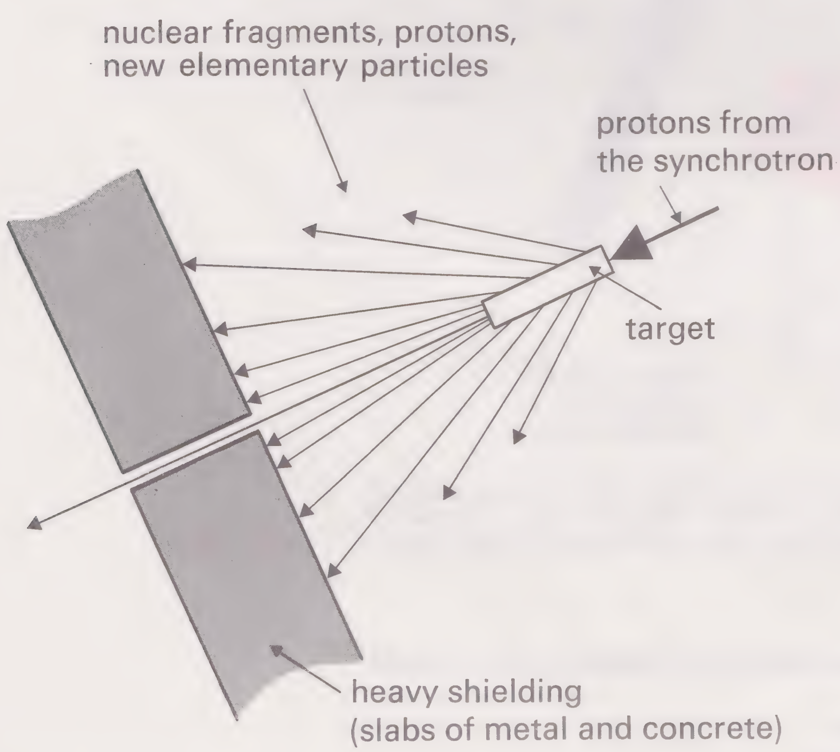

Figure 20 A slit in a heavy shielding separates out those particles moving in one given direction. All other particles slow down and undergo interactions in the material of the wall.

Which of the following characteristics do you expect for the particles emerging from the hole:

(i) same or different masses?

(ii) same or different momenta?

(iii) same or different electric charges?

(iv) same or different directions?

(i) different

(ii) different

(iii) different

(iv) same

In the next step, one can separate out the particles according to their momenta.

How could this be done?

This is achieved with a magnetic field. You will remember in the discussion of the synchrotron we mentioned that the radius of the curvature given to the path of a moving charged particle by a magnetic field was proportional to the particle's momentum. A vertical magnetic field therefore fans the particles out in a horizontal plane, as in Figure 21. The magnetic field also provides an additional bonus—it separates out particles according to their electric charge. The particles generally carry either one unit of positive charge (like the proton) or one unit of negative charge (like the electron) or are electrically neutral. If the positively charged particles are deflected to the right, then the negatively charged ones go to the left, and the neutral ones straight on.

A slit in a second heavy shielding wall is introduced and this gives rise to further selection (Fig. 22).

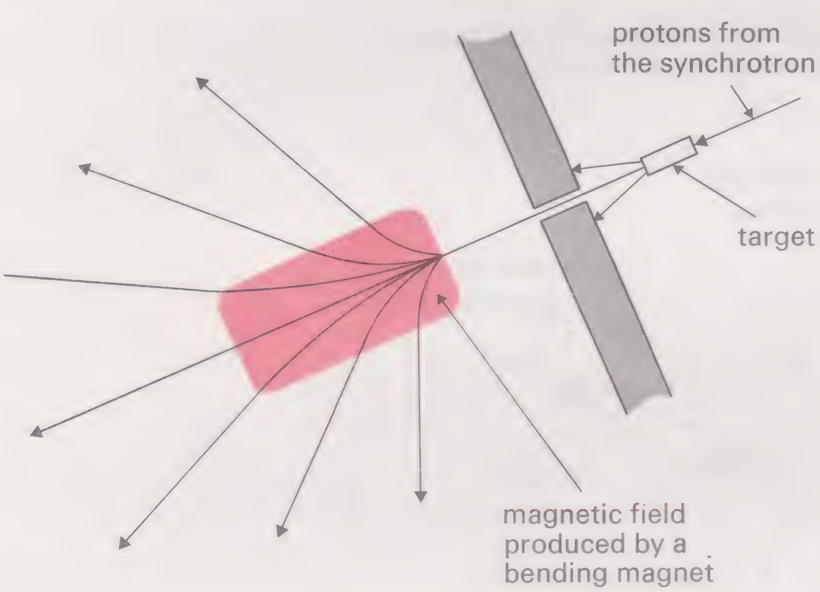

Figure 21 *A magnetic field, on the far side of the shielding wall from the target, deflects the particles according to momentum and electric charge. We show a selection of trajectories. This deflection is achieved with an electromagnet called a bending magnet.*

bending magnet

Which of the following characteristics do you expect for the particles emerging from the second slit:

(i) same or different masses?

(ii) same or different momenta?

(iii) same or different electric charges?

(iv) same or different directions?

(i) different
(ii) same
(iii) same
(iv) same

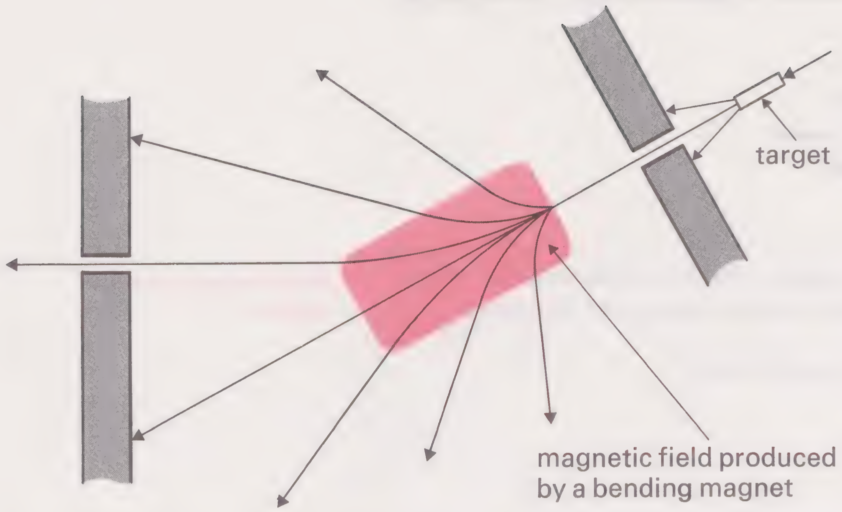

Figure 22 A second slit allows further selection of the particles to be made.

It is now necessary to separate the particles according to their mass. This can be done by a method analogous to that used in a mass spectrometer. In that instrument, as you may recall from Unit 6, ions of unequal mass were separated by first subjecting them to an electric field and then to a magnetic field. The particles from the synchrotron have already passed through a magnetic field; it remains for them now to be subjected to an electric field.

electrostatic separator

The particles are passed through the electric field of an *electrostatic separator*. As they move between two charged parallel metal plates, they are deflected sideways by an electric field acting perpendicular to the direction of motion of the particles. The particles all experience the same force because they all have the same electric charge.

Does this mean they are deflected in the same way?

They are not deflected in the same way, because particles of the same momentum but different mass move with different velocities and so spend different times within the region of the influence of the electric field. The result is that the particles are separated according to their mass (see Fig. 23).

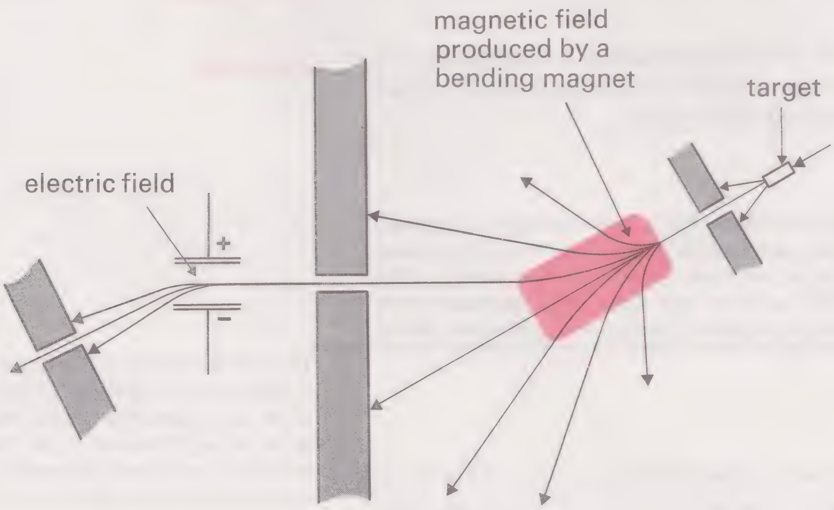

Figure 23 The final stage in the sorting out procedure is performed by an electrostatic separator. In this instrument the particles pass through an intense electric field, and are deviated once more.

Which of the following characteristics do particles emerging from the third slit in Figure 23 possess:

(i) same or different masses?

(ii) same or different momenta?

(iii) same or different electric charges?

(iv) same or different directions?

The desired goal has now been reached—the final beam consists of particles of the same mass, momentum, electric charge, and direction.

final selection of particles completed

You might at this point like to try SAQs 8 and 9.

32.3.2 The bubble chamber

If the properties of elementary particles are to be investigated, not only do they have to be produced and separated, but their subsequent behaviour must be studied. The problem now becomes one of observation. How is it possible to see a particle as small as a nucleus travelling with speeds approaching that of light?

The high-energy physicist has in fact several tools to choose from. You were introduced to two of them in the TV programme of Unit 2; one was a cloud chamber and the other a scintillation counter. In Unit 31 you came across a third—a Geiger counter.

In order to render visible something as minutely small as a sub-nuclear particle, these and other detecting instruments must exploit some kind of instability. The general idea is rather similar to what happens in a forest fire. It starts from something very small like a lighted cigarette end. This in itself, of course, does not provide much of the energy of the conflagration—that is to be found in the dried up leaves and trees. The significance of the cigarette end is that it gets the process started; without it the fire would not have begun.

So it is with particle detectors; each of them depends upon some kind of instability. The effects produced directly by the sub-nuclear particle are tiny, but they are sufficient to initiate a large-scale process.

As we said, there are several types of instrument in use. Each has its own characteristic advantages and disadvantages. We shall concentrate on just one of these techniques—one of the more important called the *bubble chamber*.

bubble chamber

The type of instability used here is that of *superheating*. A liquid is said to be superheated when its temperature is above boiling point and a small disturbance of some kind will start the liquid boiling.

superheating

Try this experiment.
Take the boiling tube supplied in the Home Kit (it is the tube packed separately from the other test tubes), put some water in it, and heat it over the burner. Eventually the water will start to boil. Look carefully at the manner in which the water boils. Do the bubbles start to grow from points anywhere within the volume of water, or do they start growing in only certain preferred places?

The bubbles start growing where the liquid comes into contact with the walls of the tube rather than in the interior of the liquid. Moreover if you look carefully you will see that certain specific points on the walls of the tube

In order for a bubble to grow it must generally have some 'centre' from which to start. Usually this consists of some irregularity in the containing vessel—a sharp corner where the sides join or perhaps an imperfection in the surface. *Ionized atoms can also provide suitable centres for bubble growth.* As a charged particle moves through a liquid, its electric charge

ionized atoms can provide suitable centres for bubble growth

interacts with that of the electrons belonging to the atoms of the liquid lying in its path, and some of the atoms are ionized. The energy deposited in this process gives rise to localized heating. So the charged particle in effect leaves a trail of 'hot spots'. If the liquid is already superheated, the extra high temperature along the particle's path can be sufficient to cause bubbles to start to grow.

seem to be preferred over others; they give rise to an almost continuous stream of bubbles. These are places where there might be a speck of dust or an imperfection in the glass surface. If an object with sharp edges or points (a pin, or match stick, for example) is dropped into the water, then the bubbles will tend to grow from the object.

In a bubble chamber, the liquid is superheated, not by increasing its temperature, as you did with the water in the boiling tube—that would be rather slow—but by suddenly decreasing the pressure acting on it. *The temperature at which a liquid boils depends on the pressure.* If the pressure is suddenly lowered, the boiling-point temperature is lowered to the value appropriate to the new reduced pressure. In a bubble chamber, it is arranged that the temperature of the liquid (which remains essentially constant) is below the higher boiling point corresponding to the initial higher pressure, but above the lower boiling point corresponding to the lower final pressure. In this way the liquid can be *abruptly* thrown into a superheated state.

the temperature at which a liquid boils depends upon the pressure

Now try Home Experiment No. 1, which demonstrates this method of producing a superheated state. In it you will use cold water to boil hot water!

A bubble chamber consists of a hollow metal chamber with glass windows in the side for viewing the bubbles. It contains a transparent liquid (usually liquid hydrogen). Bubbles in the liquid can be illuminated by light flashes and photographed with a stereocamera (Fig. 24). The sequence of operations in a bubble chamber can be summarized as follows:

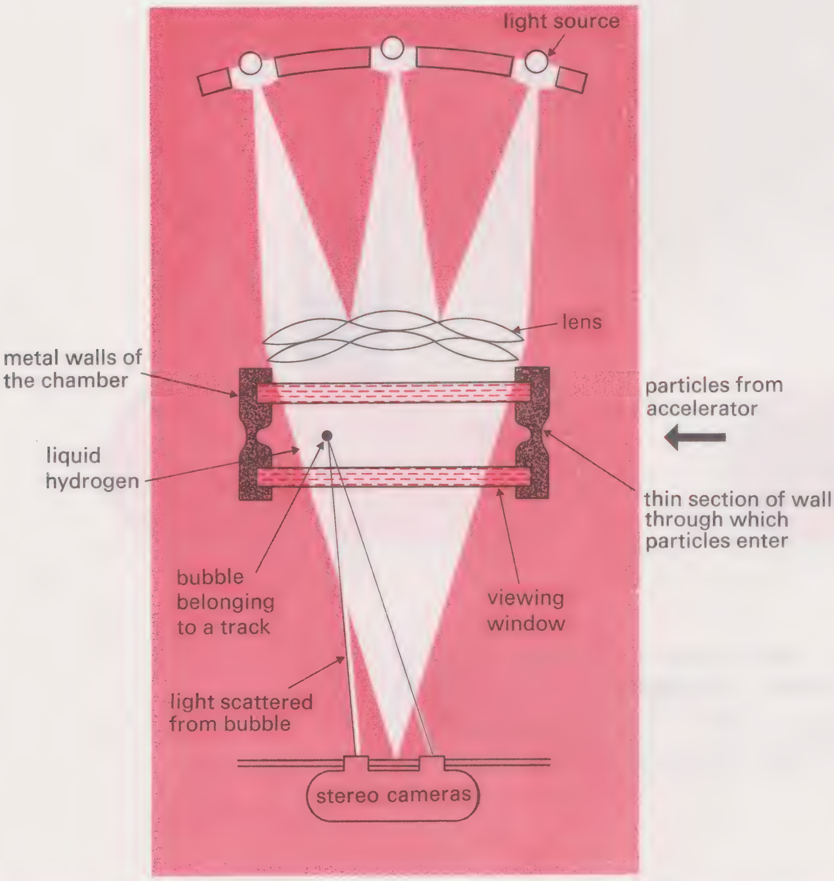

Figure 24 A simplified plan view of the optical system of the CERN 2-metre hydrogen bubble chamber. Light from three sources is concentrated by lenses in such a way that normally it misses the cameras. Bubbles interrupt this light and scatter it to the cameras, thus giving an image.

(i) A short while (about 10 milliseconds) before the particles are due to arrive from the accelerator, the pressure on the liquid is released by raising a piston (Fig. 25 (a)).

(ii) The particles pass through the thin metal wall of the chamber and into the liquid. They ionize the atoms of the liquid in their path and this process gives rise to local 'hot spots' (Fig. 25 (b)).

(iii) Bubbles start to grow from the 'hot spots' and continue to do so until they reach a visible size, whereupon the lights are flashed and stereophotographs of the bubble tracks are taken (Fig. 25 (c)).

(iv) The pressure is reapplied so as to collapse the bubbles (Fig. 25 (d)).

(v) The chamber is now ready to start another cycle.

You might at this point like to try SAQs 10 to 12.

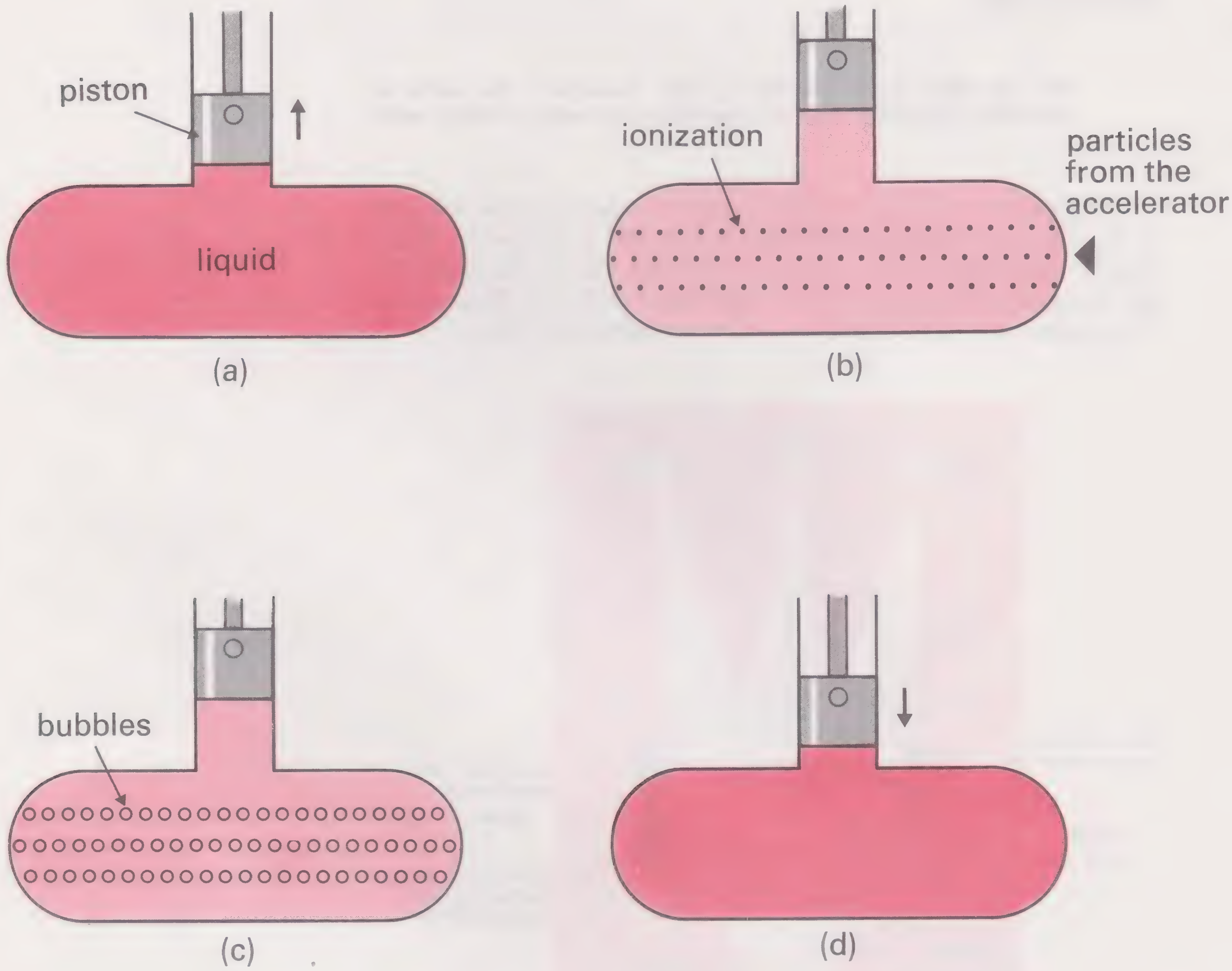

Figure 25 The sequence of operations in a bubble chamber. (a) The piston is raised, so releasing the pressure on the liquid and making it superheated. (b) Particles from the accelerator pass into the chamber and ions are formed. (c) In a few milliseconds the bubbles grow to a visible size. Stereophotographs are now taken by flashing the lights. (d) The piston is lowered to its original position, so restoring the initial pressure. The bubbles collapse.

32.4 A Look at Elementary Particles

In section 1, you were introduced to the ideas of Yukawa. At that time they no doubt appeared rather strange and abstract to you—far too 'theoretical' to have much to do with the 'real' world. We now take up the story again, but this time from a different point of view. Now we can show you the fascinating world of elementary particles as seen by the experimental physicist—as it is revealed in his detecting instruments and in particular in the bubble chamber.

For this purpose you will need the View-master supplied in the Home Experiment Kit; you will also need the reel of stereophotographs of a hydrogen bubble chamber entitled 'Reel 1, Detection of Nuclear Particles'. Insert the reel in the View-master such that the arrow pointing to the letter 'V' is at the top (Fig. 26 (a)). Depress the lever on the right-hand side of the viewer; this should bring up the first picture (Fig. 26 (b)).

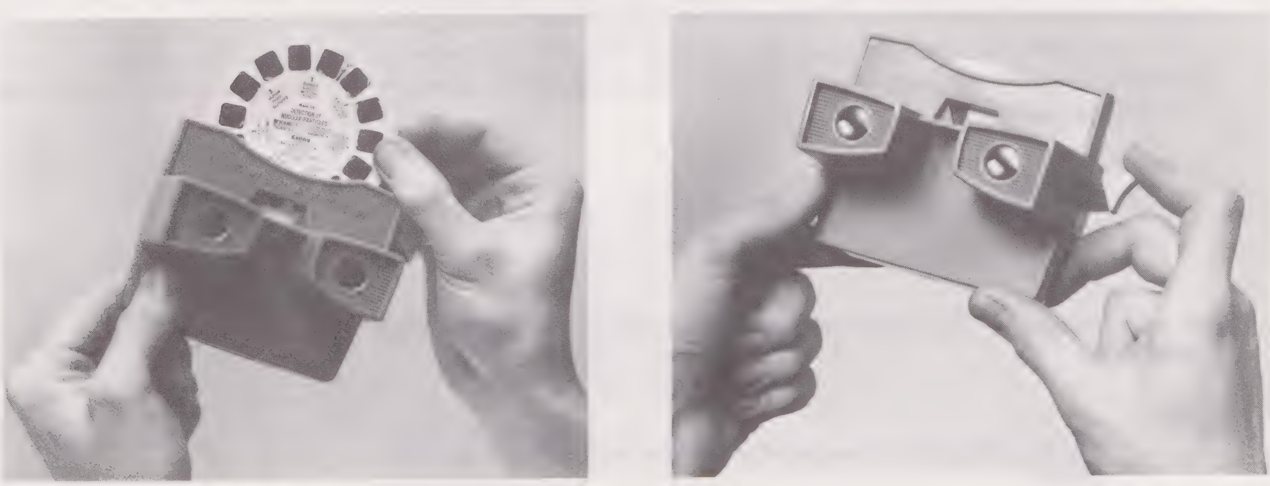

Figure 26 How to load your View-master with the reel of bubble-chamber photographs.

The number of the picture and its title appear in the gap under the name 'VIEW-MASTER'. To see the pictures, you should hold the viewer up to a window or other reasonably strong source of light (Fig. 27).

Figure 27 Hold the View-master up to a good source of light.

(Some people have a little difficulty at first in fusing the two pictures into a three-dimensional image—so be prepared to persist at it for several minutes. If you still have difficulty, it is conceivable that your eyes may be set unusually close together or wide apart. If this is the case you will not be able to see through both lenses at the same time. This will deprive you of the three-dimensional effect; but you will still be able to appreciate most of what is going on if you look through each lens separately.)

To move from one picture to the next, depress the lever on the right-hand side of the viewer.

32.4.1 Some general features of bubble-chamber photographs

Most people find bubble-chamber photographs very confusing at first. So before moving on to the more interesting events, let us just point out a few common features to help you feel more at home. Take a look at the first stereopicture.

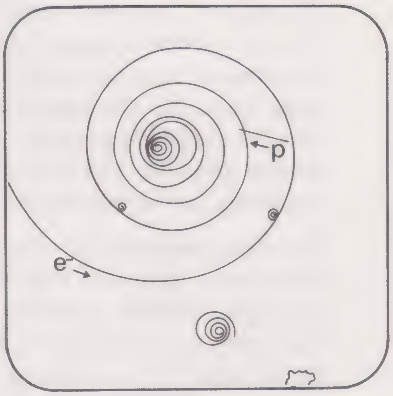

Figure 28 *Diagram for stereophotograph No. 1: spiralling electron.*

No. 1 *Spiralling electron and stray proton*

(See Fig. 28.)

The picture is dominated by an electron that enters the chamber from the left-hand side and spirals to rest. The curvature is produced by a magnetic field acting over the whole area of the chamber. The lines of magnetic induction are directed along the line of view. *Nearly all bubble chambers are provided with such a magnetic field.*

bubble chambers are provided with magnetic fields

What information can be gained about the particle from the curvature of its track?

A measurement of the curvature yields an estimate of the particle's momentum.

momentum determination

Why does the radius of curvature of the electron track become progressively smaller?

As a charged particle moves through the liquid it continually loses energy in ionizing the atoms lying in its path. Its momentum decreases and so also must its radius of curvature in the magnetic field. This continues until the particle either leaves the chamber or comes to rest in the liquid.

In the process of ionizing the atoms of the liquid along its path, the moving particle is, of course, ejecting electrons from their parent atoms. Sometimes an atomic electron is ejected so energetically that it forms a bubble track of its own. When this happens, the track of the incident particle is seen to sprout a tiny spiral from its side. You can see two of these small spirals attached to the main electron track. Watch out for further examples in later pictures.

Towards the bottom of the picture you can see another spiralling electron. Unlike those you have considered so far, this electron track starts off in the liquid for no apparent reason. In fact you are looking at an example of the Compton scattering effect (Unit 29). A high-energy photon moving through the liquid collided with one of the atomic electrons and hit it so hard that the electron formed the track you see.

But where is the track of the photon?

Photons leave no tracks. In common with the other uncharged particles, they can leave no trail of ionization behind them, and therefore no centres upon which bubbles could form.

The interpretation of bubble-chamber photographs therefore involves making allowances for unseen neutral particles.

neutral particles leave no tracks

Just above and to the right of the middle of the picture is a short straight track starting and ending in the liquid.

How does its momentum compare with that of the electrons you have been looking at?

The straightness of the track indicates that the particle causing it had a much higher momentum than that of the electrons. In fact, the particle was a proton. Initially it was the nucleus of one of the hydrogen atoms of the liquid. It was probably struck by a fast neutron entering the chamber (the neutron leaving no track because, of course, it is uncharged).

Finally note the plume of bubbles growing at the very bottom of the picture (looking rather like the mushroom one associates with a nuclear bomb explosion). This is an example of bubble growth from some physical feature of the walls of the containing vessel. You will see other examples of this spurious boiling on some of the later photographs.

Now move to the next stereophotograph.

No. 2. *Proton Scattering*

(See Fig. 29)

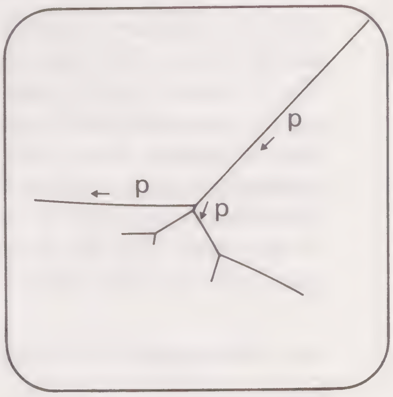

Figure 29 *Diagram for stereophotograph No.* 2*: proton scattering.*

A proton enters from the top right-hand corner leaving behind a continuous trail of ionized atoms. After a while it scores a direct hit on the nucleus of a hydrogen atom belonging to the liquid (by this we mean it comes within range of the strong interaction of the nucleus), and is deflected. From the collision come the two protons each leaving a track. This collision is followed by two further collisions.

interactions with the nuclei in the liquid

This photograph illustrates two distinct types of interaction that take place when a charged particle moves through matter:

(i) the frequent collisions with atomic electrons giving ionization and hence bubbles; and

(ii) the much less frequent—but more interesting—nuclear collisions.

As you have no doubt already noticed, there are also in the picture several low-energy electron tracks produced by the Compton scattering of photons.

There are about 10 particles entering the chamber from the top of the picture. These are particles associated with the beam from the accelerator. Are they positively or negatively charged?

***Clue.* Which way do the electron tracks bend?**

The track of the positively-charged particle entering from the upper right-hand corner of the picture is steadily deflected to the right by the magnetic field, whereas those of the negatively-charged Compton electrons curve to the left. The particles entering the chamber from the top of the picture move to the left, and so they must be negatively charged.

32.4.2 The conversion of electromagnetic and kinetic energy into rest-mass energy

No. 3 *Electron pair and triplet*

electron pair

(See Fig. 30)

In this picture, you can see one of the most important effects described by modern physics—the conversion of energy in the form of electromagnetic energy into energy in the form of rest-mass energy. It is sometimes referred to as the 'creation' of particles. This, however, is a little misleading because, of course, particles with rest-mass cannot be 'created' out of nothing. Their rest-mass is a form of 'potential energy' (Unit 4). So if a particle is to be produced, some already-existing energy in another form has to be transformed into the necessary rest-mass energy. Strictly speaking, we are concerned with *transformation* rather than creation.

energy transformations

A high-energy photon when it passes into an electric field can be transformed into a pair of electrons. One is negatively charged and is like any ordinary electron, the other has a positive charge and is either called a positive electron or a *positron.**

Note that the law of conservation of electric charge is satisfied, because the net charge of the final particles is zero, like that of the original photon. The V-shaped pair of tracks towards the upper left-hand corner of the picture is an example of such an electron pair. It has been produced by a photon passing close to the nucleus of an atom of the liquid and thus passing through the electric field associated with the charge on the nucleus. The lower triplet consists of a similar pair produced in the electric field of an atomic electron; in the process, the atomic electron is knocked on and forms the third track.

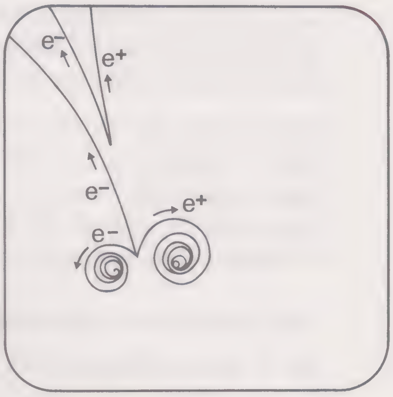

Figure 30 *Diagram for stereophotograph No.* 3*: electron pair and triplet.*

No. 4 *Four-pronged interaction*

(See Fig. 31)

Here you can see the conversion of kinetic energy into rest-mass energy, and rest-mass energy into electromagnetic energy.

A beam of negatively-charged pions enters the chamber from the lower side. These are particles produced in collisions involving protons from the accelerator. They have been separated out from the other particles coming from the target by the methods described in section 32.3. Most of the pions pass straight through the chamber and out the other end. One, however, comes within range of the strong interaction of the nucleus of a hydrogen atom, and four charged particles emerge from the resulting collision. These comprise a proton and pion *plus* two more pions, one negatively charged and the other positively charged. Some of the kinetic energy of the original pion has been transformed into rest-mass energy for the two additional particles. Measurements made on the curvatures of the tracks allow the momenta and hence energies of the particles to be determined. These measurements show that Einstein's famous equation $E=mc^2$ holds (Unit 4).

the production of pions

The process can be conveniently summarized in the form of an equation:

$$\pi^- + \mathrm{p} \rightarrow \pi^- + \mathrm{p} + \pi^+ + \pi^- \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

In these equations, each particle is represented by a symbol: p for proton is already familiar to you, and the Greek letter π (pi) represents the pion. The $^+$ and $^-$ signs indicate the sign of the electric charge of the particle.

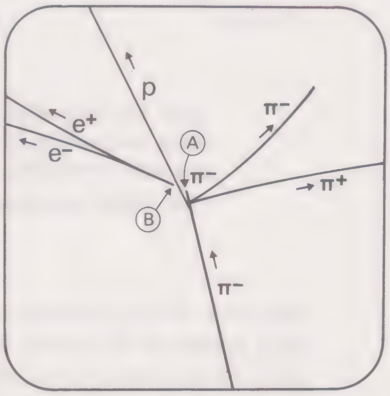

Figure 31 *Diagram for stereophotograph No.* 4*: four-pronged interaction.*

* *You first came across positrons in the Broadcast Notes of Unit* 2.

(It is always taken for granted that the proton has positive charge, so no one ever bothers to put a $^+$ sign on the p.) It is not necessary to specify *how much* negative or positive charge a particle has, because electric charge only comes in multiples of the charge on the electron. If the same symbol is used in denoting more than one particle, e.g. the symbol π in π^+ and π^-, then it is to be understood that the particles are more or less identical apart from the electric charge they carry.

You will notice that one of the π^-s from the reaction represented by equation 5 (partially obscured by the proton track) does not get very far before it interacts with another proton (at point A in Figure 31). It loses its charge to become neutral:

$$\pi^- + p \rightarrow \pi^0 + n \quad (6)$$

(Note that a zero sign is needed to specify that the final pion is neutral. It is, however, customary to omit the zero sign for the neutron because it is such a well-known particle and can only be neutral.) Pions are unstable particles; they live only a very short time before decaying into something else. As you will learn in your main experiment for this Unit (Home Experiment No. 2), charged pions decay into muons; this happens in about 2×10^{-8} s. The π^0 lives for an even shorter time, 10^{-16} s. Before it can move any detectable distance (while it is essentially still at point A), it decays into two high-energy photons called gamma rays (represented by the symbol γ):

$$\pi^0 \rightarrow \gamma + \gamma \quad (7)$$

the fast decay process $\pi^0 \rightarrow \gamma + \gamma$

In this process, the rest-mass energy of the π^0 converts into energy in the form of two flashes of light, i.e. into electromagnetic energy.

What happens to one of the photons from the π^0 in your stereophotograph?

One of the photons produces an electron pair at point B in Figure 31 (the conversion of electromagnetic energy into rest-mass energy again).

No. 5 A neutron interaction

(See Fig. 32.)

A π^- enters the chamber and interacts with a proton to produce a π^0 and a neutron:

$$\pi^- + p \rightarrow \pi^0 + n \quad (8)$$

This is the same as what happened at point A in Figure 31, but this time both γs from the decay of the π^0 leave the chamber without giving electron pairs. The neutron however collides with a proton and produces another particle—a negative pion. Electric charge is conserved by the neutron becoming a proton:

$$n + p \rightarrow p + p + \pi^- \quad (9)$$

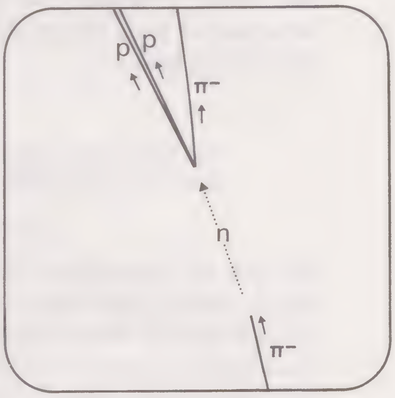

Figure 32 Diagram for stereophotograph No. 5: a neutron interaction (an interaction is sometimes called a 'star' as it is on this reel).

At this point, we interrupt our commentary to make a general remark. As you will probably have gathered already from our study of the first five stereopictures, a bubble-chamber physicist can seemingly read an awful lot into a few trails of bubbles! How can he possibly be so confident in his interpretations? It is one thing for him to say that he knows the momentum of a track from its curvature, but how can he go on to assert that the track is that of a pion or proton?

The answer lies mostly in a detailed study of the interactions. Remember these interactions have to conserve both momentum and energy. Particles of the same momentum but different mass will have different energies.

Very often, the requirement that the total energies before and after the collision (or decay) should be equal is sufficient to establish a unique choice of masses for the various particles. And even without such detailed information, a physicist can often spot helpful clues in the picture. We give one example: the number of bubbles produced per unit length along the path of the particle depends inversely upon the square of the particle's velocity; hence the lower the velocity the greater the number of bubbles.

dependence of bubble density on particle velocity

Take another look at stereophotograph No. 5. The π^- track from the neutron interaction hits on an electron which makes its own spiralling track. Study very closely the π^- and electron tracks. Which particle was the fastest, the pion or the electron? Which particle had the greater momentum, the pion or the electron?

The electron track has less bubbles per unit length and so corresponds to the faster particle. But it also has the smaller radius of curvature, and therefore the smaller momentum. Because momentum is defined as mass $\times$ velocity, it is obvious that for a particle to have a higher velocity, but a lower momentum, it must have a lower mass. This simple observation allows one to conclude immediately that the particle producing the pion track must have been heavier than that producing the electron track.

With experience, one learns to combine information from the number of bubbles with that from magnetic curvature to estimate the mass of each particle. These ionization estimates are very rough (about ± 30 per cent), but are often good enough to distinguish between various hypotheses regarding the identity of the particle, such as, for example, between electron and pion, or between pion and proton, since the masses are so different.

32.4.3 Conservation laws

Particles appearing and disappearing, some photons giving electron pairs, others not, some collisions producing pions, others not—what does it amount to? Before we move on to the last two stereopictures let us take stock.

Is the situation as chaotic as it might seem at first sight? No. The collision and decay processes are governed by strict rules of behaviour—*the conservation laws.* One of the tasks of the physicist is to seek and understand these laws.

conservation laws

We have already made explicit mention of three conservation laws in this Unit. What were they?

The law of conservation of electric charge is one such law—it is always strictly obeyed. The law of conservation of energy is another such law—it too is always obeyed (assuming of course, that the appropriate energy, given by the equation $E=mc^2$, is assigned to the rest-masses of all particles, and that a long time is available for measurement). Conservation of momentum is a third law that you know about (Unit 3). You probably did not realize it, but in our interpretation of the photographs we were also making use of yet another conservation law. If you look back over the various processes described in this section—and also the radioactive decays of Unit 31—you will note that the number of nucleons (i.e. the number of neutrons plus the number of protons) before and after the interaction is always the same. From this it might be concluded that there is a law of conservation of nucleons. This would not however be quite true (as you will see in the next stereopicture). You will remember from section 32.1 how we mentioned that many new elementary particles have

been discovered since the pion. Well, some of these new particles behave in certain respects like the nucleons. It becomes convenient to introduce a new name for referring to nucleons and to these new particles that behave like nucleons; they are collectively called—*the baryons*. Just as the neutron and proton are collectively called nucleons, so the nucleons and these new particles belong to the wider family of baryons. *The law of conservation of baryons says that although one baryon may change into another, the total number of baryons before and after the interaction must be the same.**

the general class of particles called baryons

the law of conservation of baryons

Pions are not baryons.

Look back over the interactions you have seen and decide whether a similar law of conservation of pions exists.

There is no equivalent law of conservation of pions. Particles that can be produced in any numbers in strong interactions, such as pions, belong to a class of particles called *mesons*.

the general class of particles called mesons

Now look at the next stereopicture.

No. 6 *Associated production of strange particles*

(See Fig. 33)

In this collision between an incoming pion and a proton you are introduced to *two* new particles, the Σ^- (pronounced 'sigma minus') and K^+ (pronounced 'kay plus'). The reaction can be written

$$\pi^- + p \rightarrow \Sigma^- + K^+ \quad \ldots\ldots\ldots\ldots\ldots (10)$$

The Σ^- particle, which is on the left of the picture, soon decays to a neutron and π^-, the π^- diving steeply away from you and out through the far wall of the chamber. Note that this is a decay *not* a collision; the Σ^- spontaneously breaks up into two decay fragments:

$$\Sigma^- \rightarrow \pi^- + n \quad \ldots\ldots\ldots\ldots\ldots\ldots (11)$$

Similarly the K^+ on the right decays:

$$K^+ \rightarrow \pi^+ + \pi^\circ \quad \ldots\ldots\ldots\ldots\ldots (12)$$

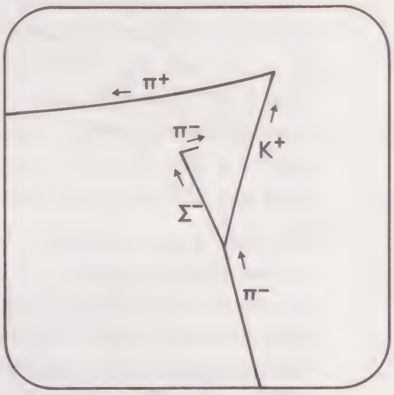

Figure 33 *Diagram for stereophotograph No.* 6*: associated production of strange particles.*

From these processes decide

(i) whether the Σ^- is a baryon or meson;

(ii) whether the K^+ is a baryon or meson.

In equation 10, the law of conservation of baryons requires that, corresponding to the single baryon present before the interaction (the proton), there should be one baryon after the interaction. Therefore *either* the Σ^- or the K^+ must be a baryon. Equation 11 tells us that the Σ^- is a baryon, since the neutron is, and the π^- is not. So the K^+ cannot be a baryon. This conclusion is confirmed by equation 12 where neither of the final particles is a baryon.

We now come to a very important observation. You may have been thinking that this photograph must be rather exceptional in that it has *two* new particles and not just one. Why did we not introduce you to these particles one at a time? Why not take, for example, the reaction $\pi^- + p \rightarrow \Sigma^- + \pi^+$? The reason is simple—*this reaction does not happen.*

* *More strictly speaking the law requires that the number of baryons minus the number of anti-baryons must remain constant. A discussion on anti-particles, though, is beyond the scope of this Course.*

Is this because it violates charge conservation or baryon conservation?

Neither of the laws is violated. There must be some other reason for the absence of this reaction.

In collisions involving only nucleons or pions, it is found from the study of many interactions that the Σ^- is *only* produced in the company of a positively charged or neutral K meson as in equation 10. Indeed, there are many other reactions that appear on the face of it to be perfectly 'reasonable'—but they also never occur. Something seems to be preventing them from happening. But what can it be?

This type of situation suggests to a physicist that some kind of conservation law is at work. To see this, first take a look at the way a more familiar conservation law operates—the law of conservation of electric charge.

This law does *not* say that it is impossible to create extra units of electric charge. It says instead that if an amount of negative electric charge is to be created, then an equal amount of positive charge must be created at the same time.

Thus, for example, in equation 9, a negative electric charge for the pion could be created because at the same time the neutron acquired an equal positive charge and became a proton.

The impossibility of producing a single Σ-particle may be analogous to the impossibility of producing a single electric charge. Perhaps the Σ-particle has some hitherto unsuspected property which, like electric charge, must be conserved. The fact that Σ-particles are always produced in association with a K^+ (or a K°) meson would then be an indication that whatever this unsuspected property might be, the K^+ (or K°) meson has an equal and opposite amount of it. Thus the simultaneous production of a Σ and a K does not alter the net amount of this property.

It is now known that this hypothesis is correct; there *is* another property of elementary particles. It has no counterpart in the macroscopic world; it cannot be identified with mass, or with angular momentum or indeed with anything that can be easily visualized. But all the evidence is that elementary particles do possess this extra property. It has been given the rather colourful name—*strangeness*.

strangeness

The K^+ is assigned $+1$ unit of strangeness; the Σ^- has -1 unit. (As with electric charge, the sign convention is quite arbitrary. Also the size of the unit is decided only on the grounds of convenience. If thought desirable, one could have assigned, for example, -72 units of strangeness to the K^+—as long as an equal and opposite amount of it was given to the Σ, i.e. $+72$ units. Incidentally, these units do not have any of the usual dimensions of Mass, Length and Time.) Pions, neutrons and protons have zero strangeness. *The law of conservation of strangeness states that strangeness is conserved in strong interactions.*

the law of conservation of strangeness

Thus in the reaction $\pi^- + p \rightarrow \Sigma^- + K^+$, the strangeness on the left-hand side is $0+0=0$ and on the right-hand side $-1+1=0$. In the non-existent reaction $\pi^- + p \rightarrow \Sigma^- + \pi^+$, the strangeness on the left-hand side would again be 0, but that on the right-hand side would be $-1+0=-1$. The reaction would violate the law of strangeness conservation, and so cannot occur.

But, you may object, what about the decay processes $\Sigma^- \rightarrow \pi^- + n$ and $K^+ \rightarrow \pi^+ + \pi^\circ$? These manifestly violate strangeness conservation. This is true, but let us draw your attention to the wording of the law; it specifically states '*in strong interactions*'. It is found that the law does *not* apply to processes in which particles spontaneously decay without colliding with anything. Other laws apply to these processes, but not the strangeness conservation law.

a restriction on the validity of the law of conservation of strangeness

How will you know whether an interaction is strong or not? In what follows, any collision with a nucleon is caused by the strong interaction;

any decay process, on the other hand, is caused by the so-called weak interaction.*

Because the strangeness law is not obeyed in decay processes, it does not have the universal validity characteristic of, say, the law of conservation of electric charge. A little messy? Perhaps, but that's the way it is!

To see how this law operates, we shall consider a few more interactions. Take for example the following observed collision process involving a nucleus:

$$\pi^+ + p \rightarrow \Sigma^+ + K^+ \quad \ldots\ldots\ldots\ldots\ldots (13)$$

From what you already know, deduce the value of the strangeness of the Σ^+.

Because it is a collision process involving a nucleon, it is a strong interaction; the law of strangeness conservation can therefore be applied. The strangeness of the left-hand side is $0+0=0$. In order for the strangeness of the right-hand side to be zero also, the strangeness of the Σ^+ must be equal and opposite to that of the K^+. Like the Σ^-, therefore, the Σ^+ must have strangeness of -1.

For another example of the way the strangeness conservation law works, take a look at the final stereophotograph.

No. 7 A K^- meson interaction

(See Fig. 34.)

A K^- meson loses its kinetic energy through ionization and stops in the liquid. It is attracted to the nearest hydrogen nucleus because of the force exerted between their opposite electric charges. On coming within range of the strong interaction of this proton, the K^- meson undergoes the following reaction:

$$K^- + p \rightarrow \Sigma^+ + \pi^- \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (14)$$

(Like the Σ^- in the previous stereophotograph, the Σ^+ subsequently decays to a nucleon and pion: $\Sigma^+ \rightarrow \pi^+ + n$.)

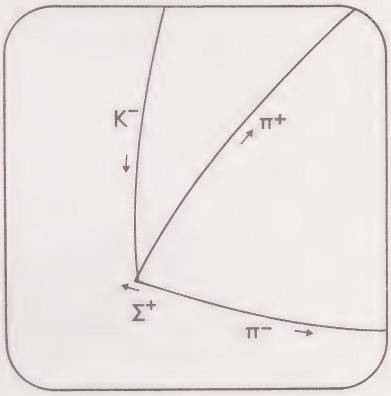

Figure 34 Diagram for stereophotograph No. 7: a K^- meson interaction.

From what you already know, deduce the strangeness of the K^- meson.

The K^- is involved in a strong interaction, so strangeness must be conserved. The strangeness of the right-hand side is $-1+0=-1$. As the strangeness of the proton on the left-hand side is zero, that of the K^- must be -1.

an important distinction between the K^- and K^+

Although the strangeness of the Σ^- and Σ^+ are the same, that of the K^- and K^+ are *opposite*. Thus according to this assignment, although the process $\pi^- + p \rightarrow \Sigma^- + K^+$ conserves strangeness, the very similar-looking process $\pi^- + p \rightarrow \Sigma^+ + K^-$ does *not*. (The left-hand side has zero strangeness, the right-hand side has $-1+-1=-2$.) Therefore, a consequence of the law of conservation of strangeness is that one can never hope to see a picture, analogous to stereophoto No. 6, in which the charges on the Σ and K are interchanged! This remarkable conclusion is found in practice to be fully vindicated. Although hundreds—perhaps thousands—of examples of $\Sigma^- K^+$ production have been studied, no one has ever come across an example of $\Sigma^+ K^-$ production.

** This is not a general rule, but it will be true of the collisions and decays we shall be considering subsequently in this Unit.*

Thus, having used a few reactions to establish the strangeness values of the new particles, one can then go on to use these values to make predictions concerning the occurrence or otherwise of all other possible reactions. We have given you two examples; there are many others we could cite. This predictive ability is one of the important features of the law of conservation of strangeness.

For further practice in handling baryon and strangeness assignments and in making predictions try SAQs 13 *to* 17.

32.5 The Theory of Elementary Particles

32.5.1 A classification scheme for elementary particles

Sifting through millions of interactions every year, physicists are continually discovering new particles and testing their behaviour. In ways similar to those you have just been using, they deduce for each new particle whether it is a baryon or meson, whether its strangeness is 0, -1, $+1$, -2, etc., as well as some other properties we have not been able to include in our brief introduction to the subject. For each new particle a catalogue of properties is compiled. Some of them have familiar everyday counterparts: mass, electric charge, etc.; others such as strangeness have no macroscopic counterpart, but are vital nonetheless to an understanding of the particle's behaviour. As accelerator energies increase, so it becomes possible to add more and more particles to the list.

But is this all there is to it—just a catalogue of particles and their properties? No, this is only the beginning. The next step is to classify them. Just as Mendeleev's Periodic Table brought order to the list of elements and their properties, so the physicist seeks to bring order to the list of elementary particles. This is no easy task—there are so many possible classification schemes one could think of. For example, should the particles be classified into baryons and mesons? If so one ought to separate n, p, Σ^-, from π^+, π^-, K^+, and K^-. Or should the classification be according to strangeness? In that case, n, p, and π^0 for example would go together (with strangeness zero), and so would Σ^-, Σ^+, and K^- (with strangeness -1). If the classification is according to electric charge then p, Σ^+ and K^+ would be members of one grouping, and n, π^0, and K^0 members of another.

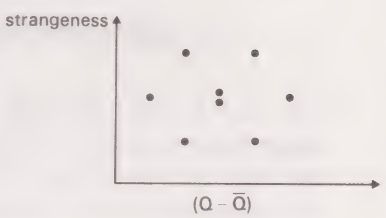

Figure 35 According to the SU3 scheme, groupings of eight particles form a hexagonal array on a plot of strangeness versus $(Q-\bar{Q})$.

In 1961, Gell-Mann in the United States and Ne'eman who was working at the time in England, simultaneously achieved a breakthrough with a theory called 'SU3'.*

the SU3 theory

According to this scheme the particles divide themselves into groupings of one, eight and ten particles each, where the particles in each grouping are characterized by having certain properties in common. One of these properties, for example, is spin. Particles may spin much in the same way as the Earth spins about an axis passing through its centre. In order for particles to belong to the same grouping, they must each spin with the same angular momentum. Likewise particles of the same grouping must be either all baryons or all mesons.

the particles in an SU3 grouping have certain properties in common—but in other ways they differ from each other

However, in some respects the particles in a grouping are *not* identical. Indeed, the way in which the particles *differ* from each other is especially interesting. This can best be seen by displaying the members of a grouping on a two-dimensional grid or graph, on which is plotted two properties that the particles do not have in common. When each particle is assigned to its location on the graph, the grouping forms a characteristic pattern. All groupings of eight particles have the pattern seen in Figure 35. The ordinate gives the value of the strangeness of the particle, and plotted along the abscissa is the value of another property of elementary particles: $(Q-\bar{Q})$. Though we hesitate to introduce yet another property, we feel

another property of particles: $(Q-\bar{Q})$

* *SU3 is the name of a mathematical 'group'. Unfortunately, without a knowledge of group theory one cannot really understand the significance of the name—'Special Unitary group 3'.*

justified in this case because its meaning is very easy to understand. This meaning is best illustrated by an example.

There are two types of nucleon—the proton and the neutron. One is positively charged, the other neutral. The 'average charge', $\overline{Q}$, of the nucleons is then given by

$$\overline{Q} = (1+0)/2 = +\tfrac{1}{2}$$

Q is simply the charge on the individual particle. Therefore in the case of the proton, for which $Q=+1$,

$$(Q-\overline{Q}) = (1-\tfrac{1}{2}) = +\tfrac{1}{2}$$

What is the value of $(Q-\overline{Q})$ for a neutron?

For a neutron $Q=0$, so

$$(Q-\overline{Q}) = (0-\tfrac{1}{2}) = -\tfrac{1}{2}$$

Given that there are three types of Σ-particles, Σ^+, Σ^0, and Σ^-, what is the value of $\overline{Q}$ for Σ-particles?
What is the value of $(Q-\overline{Q})$ for each individual Σ-particle?

The three types of Σ-particle have charges $+1$, 0 and -1 respectively. Therefore

$\overline{Q} = (+1+0-1)/3 = 0/3 = 0.$

Thus $(Q-\overline{Q})$ has the following values—

For the Σ^+: $(+1-0) = +1$

For the Σ^0: $(0-0) = 0$

For the Σ^-: $(-1-0) = -1$

For further practice in assigning values of $(Q-\overline{Q})$ to particles, try *SAQ* 18.

The idea is that, although the particles in each grouping have *some* properties in common (e.g. they may all be baryons), the values of strangeness and $(Q-\overline{Q})$ differ. When the particles are displayed on a plot of strangeness versus $(Q-\overline{Q})$, the groupings of eight form a hexagonal array, with two particles at the centre (see Fig. 35). The particular grouping to which the nucleons belong is shown in Figure 36. You can see that they are lumped together with the Σ-particles—and also the Λ and Ξ particles, which you met in *SAQ* 13.

Using the values of strangeness and $(Q-\overline{Q})$ which you have deduced for these particles in *SAQ*s 13 and 18, check that they are in their correct locations on this graph.

the neutron and proton are no more fundamental than the other elementary particles

Figure 36 shows that under this scheme, nucleons, despite their abundance in the world, have no privileged position; *the Λ, Σ, and Ξ particles are every bit as important, basic and essential as the nucleons.*

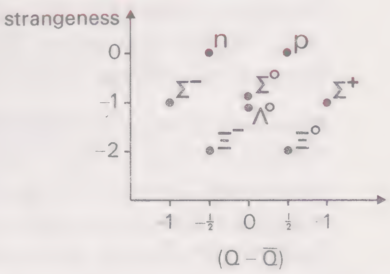

Figure 36 A particular grouping of eight particles.

Figure 37 shows the general form of the array corresponding to a grouping of ten particles; it is triangular. An example of a grouping of particles that almost fits this form of array is given in Figure 38.

Without worrying about the symbols denoting the names of the particles, do you notice what is different between Figures 37 and 38?

The odd thing about Figure 38 is that the apex of the triangle is missing—a tenth particle is needed to complete the array. This is how it was in 1962 regarding this grouping.

a similarity with the Periodic Table

Can you see a resemblance between this situation and that in which Mendeleev found himself when compiling the Periodic Table of elements? He too discerned groupings; he too found that certain members were missing. Mendeleev left gaps for undiscovered elements. Indeed he went further and *predicted* the existence of these elements and, from the location of the gaps, specified the likely properties of these elements.

Can we do the same? Can we predict, on the basis of Figure 38, the existence of a new particle, and from the location of the gap, specify in advance what its properties might be? Or is the gap merely evidence that the SU3 theory is wrong?

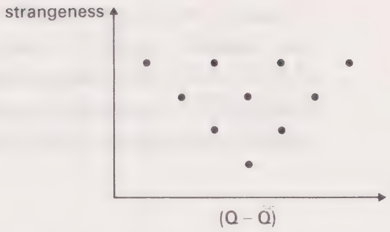

Figure 37 According to the SU3 scheme groupings of ten particles form a triangular array on a plot of strangeness versus $(Q-\overline{Q})$.

Take another look at Figure 38 and predict the following properties of a possible tenth particle:

(i) the value of its strangeness;

(ii) the value of $(Q-\overline{Q})$**;**

(iii) the value(s) of its electric charge.
(To be able to hazard a guess as to what the last property might be, you need to study the values of the electric charges on the other particles. Note that the two plus signs associated with the extreme right-hand member of the top row mean that it has a positive charge of two units—in this respect it is unusual.)

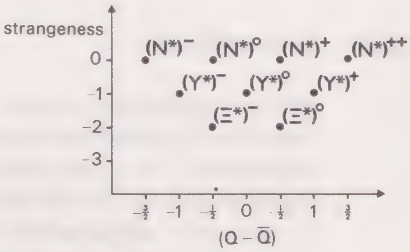

Figure 38 Can these particles be members of a grouping of ten particles?

From the position of the gap in Figure 38, the missing particle clearly must have a strangeness of -3 units, and a value for $(Q-\overline{Q})$ of zero. Its electric charge is -1 unit; this can be inferred from the fact that the left-hand member of each row is negatively charged (and the missing particle is the left-hand member of a row of one!) In this way, the suggested particle came to be called the *omega-minus* particle (Ω^-).

omega-minus

How about the mass of the Ω^-? Do the masses of the other particles in the array hold out any clues as to what this might be? Well, it is found that all members of a horizontal row have the same mass to within a few MeV (of rest-mass energy). The masses of the particles in each successive row are as follows:

N*	1 238	MeV
Y*	1 385	MeV
Ξ*	1 530	MeV
Ω^-	?	

Can you make a reasonable sort of guess as to what the mass of the Ω^- **might be? (Because of the differences between individual members of a horizontal row, you cannot expect to get closer than a few MeV. Note also we are *only* asking for a guess.)**

The difference between the masses characteristic of the first two rows is $1\,385-1\,238=147$ MeV; the difference between the second and the third is $1\,530-1\,385=145$ MeV. These two differences are the same (to within the few MeV accuracy to which we are working). It is therefore tempting to suggest that the difference in mass between the last two rows (i.e. between the Ξ* and the Ω^-) might be the same—about 145 MeV. That would make the mass of the Ω^-, $1\,530+145=1\,675$ MeV (to within a few MeV).

To summarize: in order to complete the array, a new particle is needed with a mass of about 1 675 MeV, carrying negative charge only, and possessing an unprecedented -3 units of strangeness. Does the particle exist? This question was to be the acid test of the SU3 theory.

A search was begun in 1962 and after two years the elusive omega-minus was indeed found. It had all the properties predicted—even its mass (1 672 MeV) was close to that expected. The discovery was hailed as a triumph for theoretical nuclear physics—one matched only by Yukawa's original prediction of the pion.*

a demonstration of the predictive power of the SU3 theory

At this point you might like to try SAQ 19.

32.5.2 A forward look

But a classification scheme, no matter how neat or how useful as an indicator of undiscovered particles, can hardly be regarded as an ultimate explanation. As you already know, the Periodic Table of elements, together with the atomic energy levels revealed by spectroscopy, were not in themselves explanations of anything—they were merely the outward signs of something much deeper and more fundamental. An explanation of the elements came only with an understanding of atomic structure in terms of nuclei and electrons (Units 6, 7, and 30). Likewise, the existence of different kinds of nuclei, together with their energy levels as revealed by nuclear spectroscopy and mass measurements, could only be explained in terms of their internal structure (Unit 31).

a similarity with nuclear spectroscopy

Now, for a third time, the physicist is faced with a similar situation. He knows the classification scheme of the elementary particles. He also knows some of their masses, and these can be regarded as 'energy levels'. The main difference between elementary-particle energy levels and those of atoms and of nuclei appears to be one of scale. Whereas differences in atomic energy levels are reckoned in terms of a few eV (Unit 6), and those between nuclear levels are of the order of a few MeV (Unit 31), the elementary particles differ in rest-mass energy by tens or hundreds of MeV.

So where do we go from here? Are the elementary particles *really* elementary or is their classification scheme and energy-level structure an outward sign of something deeper? Could the elementary particles be merely composite structures of something yet more basic? Is the proton's 'indivisibility' destined to suffer the same fate as that of the atom and the nucleus?

Does SU3 point the way to a new break-through in our understanding of the ultimate structure of matter?

The SU3 classification scheme holds out a tantalizing promise. The scheme is essentially based on three basic 'states' of strongly interacting particles. (The fact that there are three has to do with the number 3 in the name SU3.) These 'states' have been called *quarks*. But what exactly do we mean by the word 'states' as used in this context? It is very difficult to say. It is perfectly possible that they refer to nothing more than a mathematical concept. But many physicists hope that there is more to them than that; they hope that quarks will turn out to be real physical particles. (It is a little like the situation you encountered with waves. The concept of waves can be applied both to physical waves requiring a medium, like sound or earthquake waves, and also to waves that are purely mathematical like the probability waves of Unit 29 which require no medium and in that sense are not physical.)

quarks

* *The story of the omega-minus is told in this Unit's radio programme by those most closely connected with it—Dr. M. Gell-Mann and Dr. Y. Ne'eman, and also Dr. N. P. Samios who was one of the team of* 33 *physicists who made the discovery.*

The idea that quarks might be physically-detectable particles is an attractive one. The existence of quarks would allow all two hundred so-called 'elementary' particles to be described as composite structures of just three basic building blocks—the three types of quark. According to this scheme a proton would consist of three quarks tightly bound together.

Unfortunately, it has so far proved impossible to identify these quarks with any of the established particles—for one thing, quarks are expected to have electric charges of $\frac{1}{3}e$ or $\frac{2}{3}e$ (where e is the magnitude of the charge on the electron) and all known particles have charges that are integral multiples of e. A possible reason why quarks have so far eluded detection could be that they are exceedingly massive; the energies of present-day accelerators might be insufficient to produce them. But how, you may ask, can they be so massive when three of them add up to only one proton? Odd as it may seem, there is no contradiction here. Three quarks, each much more massive than a proton, could bind together with such colossally strong forces that the binding energy, and hence mass defect (Unit 31), would wipe out almost the whole of the mass of the three separate quarks! What we know as the proton mass may simply represent a tiny remnant left over after the binding energy has been subtracted from the masses of the quarks. Such a colossally strong force would also account for why no one has yet managed to break a proton apart into its separate quark constituents.

This also raises the question of whether the nuclear force might also be merely a remnant—a remnant of a much stronger quark-quark force acting in the interior of the nucleon. It is an interesting thought. After all, we know that the electrostatic attraction inside an atom, between its nucleus and its electrons, can give rise to an external force that binds atoms together to form molecules and solids and liquids. This inter-atomic force is complicated in that it has a short range and becomes repulsive at very small distances. This is very like the force acting between nucleons—so much so that you used liquid drops in Unit 31 to simulate the behaviour of nuclei. The complicated inter-atomic force has its origin in the simpler electrostatic force operating within the atom; perhaps the complicated nuclear force will one day be explained in terms of a simpler quark-quark force operating within the nucleon.

One final point we ought to mention. You saw in the previous Unit how, in order to understand the nuclear fusion processes occurring in the Sun (processes upon which our life on Earth depends), one had to study the behaviour of individual nuclei in a laboratory. In this Unit, you have been concerned with the physics of the very small; paradoxically it too may be connected with the physics of the very large. When a large star exhausts its nuclear fuel, it contracts under the influence of its own gravitational force. In the process, the kinetic energies of the particles in the star are believed to increase to values of the order of GeV. At this stage in stellar development, mesons and other elementary particles might be produced and high-energy nuclear physics would then take over on the grand scale. So particle accelerators and detectors, such as the ones at CERN, may be regarded, if you like, as man's ingenious means of looking into the fiery interior of a star in its final death throes.

In this Unit, we have covered much ground. We began by considering the nuclear force and this took us into the realm of elementary particles. We pointed out that the familiar neutron and proton were no more basic than many other particles, and indeed one is now no longer sure that these or any other known particles are really fundamental at all. And as for the nuclear force, it too may not be as basic as we thought at first. With the bigger accelerators, at present under construction, will quarks be discovered? We do not know. Will the Open University in future years be sending your successors stereophotographs of protons being smashed up into their constituents? We shall have to wait and see.

Summary

A new model for describing forces is introduced. According to this model, a force acting between two or more objects may be represented by the exchange of some intermediary between them.

This model is applied to the nuclear force. From the uncertainty relation and the known range of the force, the mass of the intermediary, called a pion, can be determined; it is 273 times the mass of an electron.

When sufficient energy is available, as it is in a very violent nuclear collision, some of it may transform into the rest-mass energy of the intermediary pion, which can thereby take on a real and separate existence.

Other particles have also been discovered. The exchange model of the force must therefore be developed further to allow the nucleon to exchange additional heavier particles during close approaches.

The study of the nuclear force, therefore, becomes the study of elementary particles.

To produce these particles, protons have to be accelerated to high energies. This is done in three stages. First of all the protons are subjected to an intense electric field. Secondly, they pass through the drift tubes of a linear accelerator and are accelerated by an alternating electric field. Finally they are accelerated to the highest energy in a synchrotron. In this machine, they are steered on a circular path by a magnetic field, and accelerated by electric fields.

The protons emerge in batches and are made to strike a target. The particles produced in these collisions are separated according to mass and momentum by a combination of slits and magnetic and electric fields.

The behaviour of the particles can be observed with a bubble chamber. In this instrument, pressure is reduced on a liquid so putting the liquid into a superheated condition. Bubbles grow on 'hot spots' left by the passage of charged particles. These can be photographed.

Through a study of stereopictures, some insight is given into the analysis of bubble-chamber tracks. The analysis of such photographs reveals that the interactions take place according to certain conservation laws—conservation laws of energy, momentum, electric charge, etc. It becomes necessary to introduce entirely new properties for the particles—properties that have no macroscopic counterpart. One such property, strangeness, is found to be conserved in strong interactions.

It has been found useful to classify the elementary particles using the 'SU3' theory. According to this scheme, the particles are displayed in arrays. The appearance of gaps in these arrays has led to the prediction of new particles—the most significant being that of the omega-minus particle.

The Unit ends on a note of speculation. Does the SU3 theory point the way to a much deeper understanding of the structure of matter? Are protons and other so-called elementary particles built up from a yet more fundamental entity—the quark?

Book List

For those who wish to pursue the subject of elementary particles a little further we suggest you consult the following books:

K. W. Ford, *The World of Elementary Particles*, 1963, Blaisdell.

H. S. W. Massey, *The New Age in Physics*, 1966, Elek.

Section 1.3

Question 1 (*Objective 1*)

(a) *True* (b) *False*

The nucleus of any element is an elementary particle.

Section 2.3

Question 2 (*Objective 2*)

(a) *True* (b) *False*

In a linear accelerator the voltage on the drift tubes increases progressively from one end of the accelerator to the other.

Question 3 (*Objective 2*)

(a) *True* (b) *False*

Hydrogen gas is led into one end of a linear accelerator and as the hydrogen atoms are accelerated towards the first drift tube they are stripped of their electrons.

Section 2.4

Question 4 (*Objective 2*)

(a) *True* (b) *False*

In a synchrotron the purpose of the magnetic field is to accelerate the protons in a direction tangential to the synchrotron ring.

Question 5 (*Objective 2*)

(a) *True* (b) *False*

Two synchrotrons, possessing magnetic fields of the same maximum strength, are such that one machine has a circumference twice that of the other. The maximum momentum of the protons from this machine is twice that of the other.

Question 6 (*Objective 2*)

(a) *True* (b) *False*

In a synchrotron, the protons are repeatedly reflected at the walls of the circular vacuum chamber, and this helps to constrain them to move on a circular path.

Question 7 (*Objective 2*)

(a) *True* (b) *False*

How much energy, expressed in joules, is contained in each batch of 10^{12} protons accelerated in the CERN machine to 28 GeV?

($1 \text{eV} = 1.6 \times 10^{-19}$ J)

Section 3.1

Question 8 (*Objective 3*)

A particle travels from a point A to a point B at constant speed through a magnetic field. It is required to send a second particle in the reverse direction from B to A over the identical path. The two particles each have an electric charge of magnitude one unit.

The particles are such that:

(i) their unit charges have (a) the same sign, (b) opposite sign?

(ii) their momenta are (a) the same, (b) not necessarily the same?

(iii) their masses are (a) the same, (b) not necessarily the same?

(iv) their velocities are (a) the same, (b) not necessarily the same?

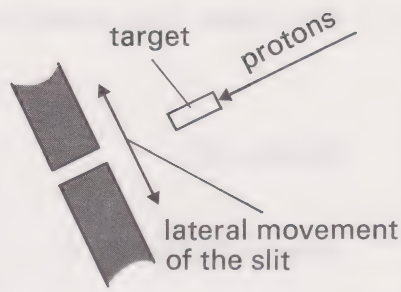

Figure 39 Diagram illustrating the direction of movement of the first slit considered in SAQ 9.

Question 9 (*Objective 3*)

Turn to Figure 23. When the slit closest to the target is displaced laterally, i.e. in the direction indicated in Figure 39, there is a gradual change in the number of particles passing through the slit. Likewise, when the second slit is displaced laterally there is a gradual change in the number of particles this slit allows through. However, a lateral displacement of the final slit gives rise to an irregular variation as in Figure 40. How do you explain these observations?

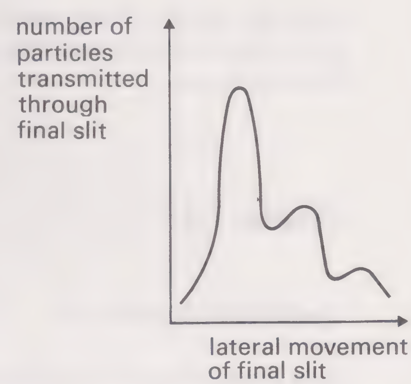

Figure 40 The variation in the number of particles transmitted by the third slit (in Figure 23) when this slit is moved laterally.

Section 3.2

Question 10 (*Objective 2*)

The pressure on the liquid in a bubble chamber is released (a) before, (b) during, or (c) after the passage of the particles?

Question 11 (*Objective 2*)

In a bubble chamber, there should be no irregularities in the walls of the container, otherwise boiling will occur on these irregularities and not along the paths of the charged particles.

(a) *True* (b) *False*

Question 12 (*Objective 2*)

The lights used to illuminate the tracks in a bubble chamber are flashed at the instant the particles pass through the chamber.

(a) *True* (b) *False*

Section 4.3

Question 13 (*Objective 5*)

In the text, you have been introduced to several particles. Some have been shown to be baryons, others mesons. Moreover, you have seen how their strangeness values are deduced. This information is summarized in Table 1.

Table 1

strangeness	*baryon*	*meson*
+2		
+1		K^+K°
0	p n	$\pi^+\pi^-\pi^\circ$
−1	$\Sigma^-\Sigma^+$	K^-
−2		

We shall quote six examples of strong interactions which have been observed, each involving a particle new to you. For each of the six new particles (shown in brackets alongside the reaction), deduce from the appropriate conservation laws whether it is a baryon or meson and what the value of its strangeness is. Record your answer by entering the symbol for the particle in the appropriate place in the table. (It is probably best to do this in pencil at first because you need a correct (!) version of Table 1 in order to be able to answer the next question.) Note that in the fourth reaction, the particle $\overline{K^0}$ (pronounced 'kay nought bar') is not to be confused with another particle, the K^0, to which you have already been introduced.

$$\pi^- + p \rightarrow n + \eta^0 \qquad (\eta^0)$$
$$K^- + p \rightarrow \Sigma^0 + \pi^0 \qquad (\Sigma^0)$$
$$K^- + p \rightarrow \Xi^0 + K^0 + \pi^0 \qquad (\Xi^0)$$
$$K^- + p \rightarrow \overline{K^0} + n + \pi^0 \qquad (\overline{K^0})$$
$$p + n \rightarrow \Lambda^0 + K^+ + n \qquad (\Lambda^0)$$
$$K^- + p \rightarrow \Xi^- + K^+ \qquad (\Xi^-)$$

Question 14 (*Objective 5*)

In order to attempt this question, you need to be able to refer to a correctly filled-in version of Table 1. So before reading on, check your answers to Question 13, and amend Table 1 as necessary.

We shall propose some hypothetical reactions and you are to decide for each whether the reaction proceeds as a strong interaction or not. If *not*, indicate which law(s) is(are) violated.

Is it a strong interaction?

	YES	NO *because it violates the law of conservation of*		
		strangeness	*baryons*	*electric charge*
$\Xi^- + p \rightarrow \Lambda^0 + \Lambda^0$				
$K^- + p \rightarrow \Lambda^0 + \overline{K^0}$				
$n + p \rightarrow \Sigma^+ + K^0$				
$\pi^- + p \rightarrow \Sigma^0 + K^0 + \pi^+$				
$p + p \rightarrow \eta^0 + \pi^+ + n + \pi^0$				
$\Sigma^- + n \rightarrow \Lambda^0 + \pi^-$				
$\Lambda^0 \rightarrow p + \pi^-$				
$\Xi^0 + n \rightarrow \overline{K^0} + \Sigma^+ + \pi^-$				
$K^+ + p \rightarrow K^0 + \overline{K^0} + K^+ + \pi^+ + n$				
$K^+ + n \rightarrow \Xi^0 + \overline{K^0} + \pi^+$				
$\pi^- + p \rightarrow \Xi^- + \overline{K^0} + \overline{K^0} + n + \pi^+$				
$\pi^+ + n \rightarrow \Sigma^+ + K^0$				
$p + p \rightarrow \Sigma^+ + K^+ + n$				

Self-Assessment Questions

Question 15 (*Objectives 4 and 5*)

(In answering this question, refer as necessary to Table 1 of Question 13.)

A K^- meson interacts with a proton at point A in Figure 41 and produces a π^+, a π^-, and one neutral particle. This neutral particle decays at point B into a positive and a negative particle.

(i) What is the strangeness of the neutral particle?

(ii) Is the neutral particle a baryon or meson?

(iii) Is the appearance of the two tracks coming away from point B consistent with the interpretation that the neutral particle decays into two particles of equal mass?

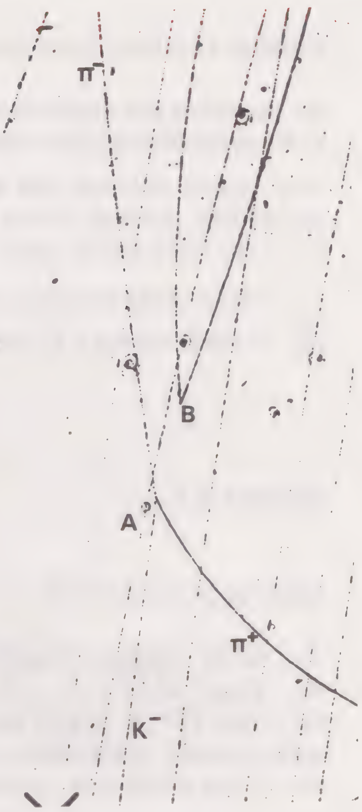

Figure 41 A bubble-chamber photograph used in connection with SAQ 15.

Question 16 (*Objectives 4 and 5*)

(In answering this question, refer as necessary to Table 1 of Question 13.)

A K^- meson interacts with a proton at point A in Figure 42. Coming from the interaction is a proton, a π^-, and one neutral particle. The neutral particle decays at point B into a π^+ and a negative particle, which for the time being we call 'X^-'.

(i) What is the strangeness of the neutral particle?

(ii) Is the negative particle, X^-, a baryon or meson?

(iii) Can you deduce the strangeness of the negative particle, X^-, by applying the law of conservation of strangeness first at A and then at B?

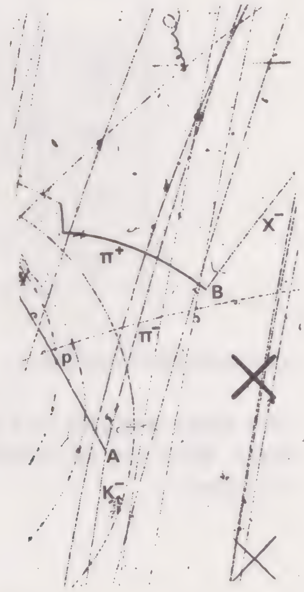

Figure 42 A bubble-chamber photograph used in connection with SAQ 16.

Question 17 (*Objectives 4 and 5*)

(In answering this question, refer as necessary to Table 1 of Question 13—as supplemented by your answer to Question 13.)

A π^- meson interacts with a proton at point A in Figure 43 to produce two neutral particles. One is a Λ^0 and this decays at B into a proton and a π^-; the other is a K meson which decays at C into a π^+ and a π^-.

(i) Which of the particles, X or Y, is the proton from the decay of Λ^0?

(ii) Is the K meson a K^0 or a $\overline{K^0}$?

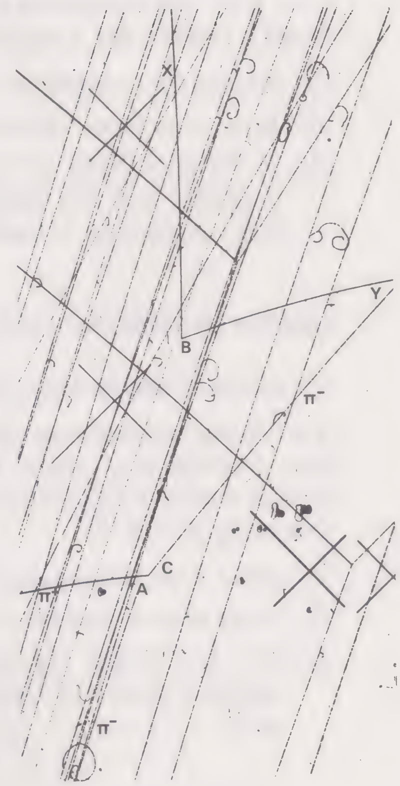

Figure 43 A bubble-chamber photograph used in connection with SAQ 17.

Section 5.1

Question 18 (*Objective 6*)

Just as the 'nucleons' consist of (n, p), the 'sigmas' of (Σ^+, Σ^0, Σ^-), and the 'pions' of (π^+, π^0, π^-), so there are other particles e.g. (Ξ^-, Ξ^0); (K^+, K^0); ($\overline{K^0}$, K^-), (η^0) and (Λ^0). Note that there are two types of K with opposite strangeness so these have to be separated. Note also that the η^0 and Λ^0 have no charged counterparts.

Calculate the value of ($Q-\overline{Q}$) for each individual particle (where Q and $\overline{Q}$ are defined in the text).

	($Q-\overline{Q}$)		($Q-\overline{Q}$)
Ξ^-		$\overline{K^0}$	
Ξ^0		K^-	
K^+		η^0	
K^0		Λ^0	

Question 19 (*Objective 7*)

The seven particles in Figure 44 almost make up an SU3 grouping of eight. What are the values of the strangeness and ($Q-\overline{Q}$) of the missing member?

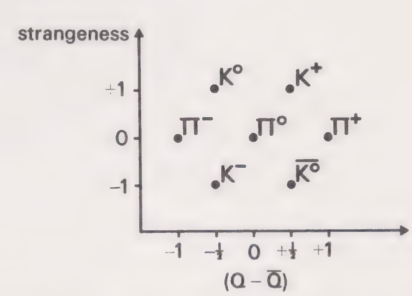

Figure 44 A grouping of particles that almost makes up an array of eight. (SAQ 19.)

Self-Assessment Answers and Comments

Question 1

Answer (b)

Comment

An elementary particle is one that cannot be broken down into more basic component parts. The nuclei of elements (except hydrogen) can be split up into their constituent neutrons and protons.

Question 2

Answer (b)

Comment

The drift tubes in Figure 9 are connected to the same alternating voltage supply, so their voltages must be the same.

Question 3

Answer (b)

Comment

The hydrogen nuclei are stripped of their electrons in the proton source, not in the linear accelerator. Until the electrons are removed, there is no way of accelerating the hydrogen atoms. The charge on the ionized atom is the 'handle' by which the electric field can get hold of the ion and accelerate it.

Question 4

Answer (b)

Comment

The acceleration is certainly in a direction tangential to the synchrotron ring, but it is produced by an electric not a magnetic field.

Question 5

Answer (a)

Comment

The circumference of a ring is $2\pi R$, where R is the radius of the ring. If one machine has twice the circumference of the other, it must have twice the radius. The path of the particles must therefore have twice the radius of curvature, and hence they must have twice the momentum. (Remember, for the same magnetic field, momentum is proportional to the radius of curvature.)

Question 6

Answer (b)

Comment

The protons are constrained to move on a circular path by the magnetic field, not by the vacuum chamber. The latter is there in order to allow the protons to move in a vacuum and so to minimize the number of protons that are scattered out of the machine before full energy has been reached.

Question 7

Answer 4 500 J

Comment

The final energy of each proton is 28 GeV i.e. 28×10^9 eV. This is the same as $(28 \times 10^9) \times (1.6 \times 10^{-19})$ joules. A batch of 10^{12} protons has energy

$$(28 \times 10^9) \times (1.6 \times 10^{-19}) \times 10^{12}\ \text{J} = 4\,500\ \text{J}$$

This is about the same as the kinetic energy of a brick dropped from the top of the Post Office Tower in London. The energy is sufficiently great that one would not want passers-by to be at the foot of the tower when the brick lands, but then again the energy is not particularly spectacular. What *is* remarkable about the energy delivered by the synchrotron is that it is concentrated into a tiny speck of matter, with a mass equivalent to 10^{-15} of a brick!

Question 8

Answer (i) b; (ii) a; (iii) b; (iv) b

Comment

As far as electric charge is concerned, a charge transferred from A to B is equivalent to an equal but opposite charge transferred from B to A. Thus, if the particle moving from A to B in Figure 45 (a) is deflected to the right, an oppositely charged particle is needed for the journey from B to A, if it is to be deflected to the left (see Fig. 45 (b)). In order that the radius of curvature should be the same, the particle travelling from B to A must have the same momentum as that going from A to B. As long as the momentum (mv) is the same, it does not matter whether the mass or the velocity are the same.

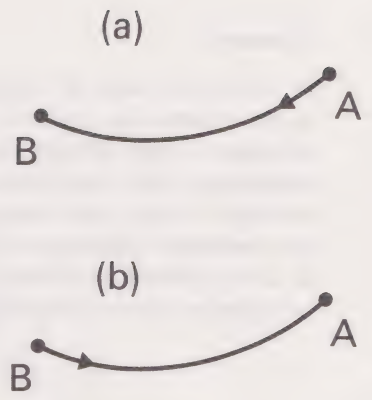

Figure 45 See the answer to SAQ 8.

Question 9

Answer

Particles are emitted from the target in all directions, so a lateral displacement of the first slit should give a smooth variation in the number of particles passing through it. Likewise, the particles passing through the field of the bending magnet have a continuous range of momentum values; thus a lateral displacement of the second slit also gives a smooth variation. However, the final selection of particles by the electric field is according to mass. Although there might be several kinds of particle in the final beam, their masses are restricted to certain values e.g. those of the pion, proton, K meson, etc. Thus, a lateral displacement of the final slit reveals a series of peaks, each one corresponding to one of these types of particle.

Question 10

Answer (a)

Comment

The pressure on the liquid is released before the arrival of the particles so that the liquid is already in a superheated state. This is because the energy deposited by the particle rapidly disperses away from the path of the particle; unless the bubbles start to grow immediately while the energy is still concentrated along the path, they cannot grow at all.
In the TV programme, you will be shown a display on a cathode-ray oscilloscope which will make clearer the relationship in time of the arrival of the beam, the flashing of the lights, and the variation of the pressure on the liquid.

Question 11

Answer (b)

Comment

In the early days of bubble-chamber development (the early 1950s) it was feared that spurious boiling on irregularities in the walls of the container would prevent boiling along the paths of charged particles. Scrupulous care was therefore taken to keep all surfaces smooth and rounded. It was soon discovered, however, that such precautions were not necessary. Although in modern chambers the walls are kept smooth so as to prevent unnecessary spurious boiling, this type of boiling does nevertheless occur to some extent—as you saw in stereophotograph No. 1.

Question 12

Answer (b)

Comment

There must be a short delay (a millisecond or so) between the passage of the particles and the taking of the photograph, in order that the bubbles may have time to grow to a visible size.

Question 13

Answer

After making your additions, Table 1 should look like this:

strangeness	*baryon*	*meson*
+2		
+1		K^+K^0
0	p n	$\pi^+\pi^-\pi^0\eta^0$
−1	$\Sigma^-\Sigma^+\Sigma^0\Lambda^0$	$K^-\overline{K^0}$
−2	$\Xi^0\Xi^-$	

Comment

While getting used to the procedure of checking a reaction for strangeness or baryon conservation, it is a good idea to draw up a table under each reaction with a row in which the strangeness value of each particle is written, and another for indicating which particles are baryons (by putting '1' for a baryon and 'O' for a meson). It is then an easy matter to balance both sides of each equation. We show how this is done for the first and sixth reactions:

$$\pi^- + p \rightarrow n + \eta^0$$

strangeness	$0+0 = 0+s$	$\therefore s=0$
baryon	$0+1 = 1+b$	$\therefore b=0$

$$K^- + p \rightarrow \Xi^- + K^+$$

strangeness	$-1+0 = s+1$	$\therefore s=-2$
baryon	$0+1 = b+0$	$\therefore b=1$

(In Question 14 you will also be required to check that the reaction conserves electric charge. You might therefore wish to include a third row under the reaction for writing down the electric charge of each particle.)

Question 14

Answer

Your completed table should look like this:

Is it a strong interaction?

	YES	NO because it violates the law of conservation of:		
		strangeness	*baryons*	*electric charge*
$\Xi^- + p \rightarrow \Lambda^0 + \Lambda^0$	X			
$K^- + p \rightarrow \Lambda^0 + \overline{K^0}$		X		
$n + p \rightarrow \Sigma^+ + K^0$			X	
$\pi^- + p \rightarrow \Sigma^0 + K^0 + \pi^+$				X
$p + p \rightarrow \eta^0 + \pi^+ + n + \pi^0$			X	X
$\Sigma^- + n \rightarrow \Lambda^0 + \pi^-$			X	
$\Lambda^0 \rightarrow p + \pi^-$		X		
$\Xi^0 + n \rightarrow \overline{K^0} + \Sigma^+ + \pi^-$			X	
$K^+ + p \rightarrow K^0 + \overline{K^0} + K^+ + \pi^+ + n$	X			
$K^+ + n \rightarrow \Xi^0 + \overline{K^0} + \pi^+$		X		
$\pi^- + p \rightarrow \Xi^- + \overline{K^0} + \overline{K^0} + n + \pi^+$		X	X	
$\pi^+ + n \rightarrow \Sigma^+ + K^0$	X			
$p + p \rightarrow \Sigma^+ + K^+ + n$	X			

Comment

If you did not fare very well, we suggest you come back to this question in a day or two and have a second go at it, covering up your previous answers. There is really nothing very difficult about it—as long as you are not careless!

Question 15

Answer

(i) The strangeness is -1.
(ii) The particle is a baryon.
(iii) The two particles do *not* have equal mass.

Comment

The reaction at point A can be written:

$$K^- + p \rightarrow \pi^+ + \pi^- + X^0$$

where the unknown neutral particle is being denoted by X^0. Conservation of strangeness requires the X^0 to have the same strangeness as the K^- i.e. -1. Conservation of baryons requires the X^0 to be a baryon.

The two particles from the decay of the X^0 are such that the positively-charged particle on the right has the greater momentum (judged from its greater radius of curvature in the magnetic field), but the lower velocity (judged from the fact that it has more bubbles per unit length than the negatively-charged particle on the left). It can only have a greater momentum (mv) and a lower velocity (v), if its mass (m) is greater than that of the other particle. In fact, the neutral particle is a Λ^0, and it decays as follows:

$$\Lambda^0 \rightarrow p + \pi^-$$

Question 16

Answer

(i) The strangeness is -1.
(ii) Particle X^- is a meson.
(iii) No.

Comment

The reaction at point A can be written:

$$K^- + p \rightarrow p + \pi^- + Z^0$$

where the unknown neutral particle is being denoted by Z^0. Conservation of strangeness requires the Z^0 to have the same strangeness as the K^- i.e. -1. Conservation of baryons at point A requires the Z^0 to be a meson. At point B the Z^0 decays thus:

$$Z^0 \rightarrow \pi^+ + X^-$$

As the Z^0 and π^+ are both mesons, conservation of baryons requires X^- to be a meson too. Although the strangeness of the π^+ is known to be zero and that of the Z^0 has been found to be -1, it is *not* possible to conclude from strangeness conservation what the strangeness value of the X^- might be. This is because the decay of the Z^0 is caused by the *weak* interaction, not by the strong interaction, and so the law of conservation of strangeness does not apply to the reaction at point B (though of course the laws of conservation of baryons and electric charge *do* apply, as always).

In point of fact the 'Z^0' is a neutral K meson and the 'X^-' is a π^-.

Question 17

Answer

(i) Particle X.
(ii) K^0.

Comment

The various electrons in the picture, as well as the incoming particles, which you have been told are negatively-charged pions, are seen to curve to the right. The proton from point B must be positively charged and so is the one that curves in the opposite direction, i.e. to the left. (If you have difficulty seeing the curvature—which is admittedly small—you should place the edge of a straight ruler alongside the track.) The reaction at point A is either:

$$\pi^- + p \rightarrow \Lambda^0 + K^0$$
$$\text{or } \pi^- + p \rightarrow \Lambda^0 + \overline{K^0}$$

By looking up the strangeness values of these particles in your supplemented version of Table 1 of Question 13, you should easily be able to verify that only the first of these equations satisfies strangeness conservation. Therefore the particle must be a K^0, and not a $\overline{K^0}$.

Question 18

Answer

	$(Q-\overline{Q})$		$(Q-\overline{Q})$
Ξ^-	$-\frac{1}{2}$	$\overline{K^0}$	$+\frac{1}{2}$
Ξ^0	$+\frac{1}{2}$	K^-	$-\frac{1}{2}$
K^+	$+\frac{1}{2}$	η^0	0
K^0	$-\frac{1}{2}$	Λ^0	0

Comment

The charge values, Q, for the Ξ^- and Ξ^0 are -1 and 0 respectively. The 'average charge', $\overline{Q}$, for these two particles is $(-1+0)/2 = -\frac{1}{2}$

$$\therefore \text{For the } \Xi^-, (Q-\overline{Q}) = (-1)-(-\tfrac{1}{2}) = -1+\tfrac{1}{2} = -\tfrac{1}{2}$$
$$\text{and for the } \Xi^0, (Q-\overline{Q}) = \quad 0-(-\tfrac{1}{2}) = +\tfrac{1}{2}$$

The two pairs of K mesons can be treated in the same way. The charge, Q, for the η^0 is 0. As η mesons only exist in the neutral form, this is also their 'average value', Q.

$$\therefore \text{For the } \eta^0, (Q-\overline{Q}) = 0-0 = 0.$$

The Λ^0 can be treated in the same way as the η^0.

Question 19

Answer

The strangeness is zero and the value of $(Q - \overline{Q})$ is also zero.

Comment

Note that in SU3 groupings of eight particles, there should be *two* particles at the centre of the array. As it stands in Figure 44, the array has only a single member in that location. The missing member has the strangeness and $(Q - \overline{Q})$ values characteristic of that location, i.e. they are both zero. The missing particle is in fact the η^0 meson. At the time Gell-Mann and Ne'eman put forward their SU3 theory, this array *was* incomplete in the way described in this question. The theory was used to predict the existence of the new particle, just as it was used to predict the existence of the omega-minus particle.

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